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NASA Conference Publication 10083

# Beyond the Baseline 1991

*Proceedings of the Space Station Evolution Symposium*

Volume 1: Space Station Freedom

Part 2

*Proceedings of a conference held at South Shore Harbour Resort and Conference Center League City, Texas August 6-8, 1991*

NASA

NASA Conference Publication 10083

# Beyond the Baseline 1991

## *Proceedings of the Space Station Evolution Symposium*

**Volume 1:** Space Station Freedom

Part 2

*Proceedings of a conference held at South Shore Harbour Resort and Conference Center League City, Texas*

National Aeronautics and Space Administration

Scientific and Technical Information Branch

1991

## Preface

This publication is a compilation of papers presented at the Second Space Station Evolution Symposium: "Beyond the Baseline 1991" from August 6 - 8, 1991. The symposium was structured as a forum to discuss the current status and future plans for Space Station Freedom (SSF). The primary purpose of the gathering was to review the plans and progress in ensuring a baseline design with the flexibility to accommodate a broad range of potential utilization demands and to effectively incorporate technology advances over the lifetime of the facility. The timing of the conference was chosen at the critical juncture between completion of the Delta Preliminary Design Reviews and the Program Critical Design Reviews.

The plenary papers describe the current status of the restructured Space Station Freedom design, the plans of the international partners, and future utilization of the facility. Related programs in advanced technology and space transportation are also discussed.

The technical sessions represent the results of tasks funded by Level I Space Station Engineering in Advanced Studies and Advanced Development. The charts presented are amplified here by facing page text. The work was accomplished in fiscal years 1990 and 1991 and was presented by those in government and industry who performed the tasks.

The results of SSF Advanced Studies provide a road map for the evolution of Freedom in terms of user requirements, utilization and operations concepts, and growth options for distributed systems. Regarding these specific systems, special attention is given to: highlighting changes made during restructuring; description of growth paths through the follow-on and evolution phases; identification of minimum-impact provisions to allow flexibility in the baseline, and identification of enhancing and enabling technologies.

The activities under Advanced Development and Engineering Prototype Development (EPD) are targeted to improve the functionality and performance of baseline systems, thus providing options to the program which reduce schedule and technical risks. These applications have the potential to improve flight and ground system productivity, reduce power consumption and weight, and prevent technological obsolescence. Products of these tasks include: "Engineering" fidelity demonstrations and evaluations of advanced technology; detailed requirements, performance specifications, and design accommodations for insertion of advanced technology, and mature technology, tools, and applications for SSF flight, ground, and information systems.

Dr. Earle K. Huckins, III
Director, Space Station Engineering
Office of Space Flight
NASA Headquarters

Listed below are the persons who made this symposium possible.

## COMMITTEE MEMBERS

**Conference Chair:**

- Earle K. Huckins III
  *NASA Headquarters*

**Program Planning Committee Technical Chairs:**

- Stephen Cook
  *NASA Headquarters*
- Gregg Swietek
  *NASA Headquarters*
- Mark Gersh
  *NASA Headquarters*
- Peter Ahlf
  *NASA Headquarters*
- Alan Fernquist
  *NASA Headquarters*

**Session Chairs:**

- Lewis Peach
  *NASA Headquarters*
- John-David Bartoe
  *NASA Headquarters*
- W. Ray Hook
  *NASA Langley Research Center*
- Karen Brender
  *NASA Langley Research Center*
- Edward Chevers
  *NASA Ames Research Center*
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- Mark Gersh
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- Alan Fernquist
  *NASA Headquarters*

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- Glenn Freedman
  *UH-Clear Lake*
- Carla Armstrong
  *Barrios Technology, Inc.*

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| 8:30 | Welcoming Remarks | Dr. Aaron Cohen<br>*Director, NASA Johnson Space Center* |
| 8:45 | Space Station Freedom:<br>An Investment In The Future | Dr. William B. Lenoir<br>*Associate Administrator, NASA Office of Space Flight* |
| 9:45 | Space Station Freedom Program Status | Dr. John Cox<br>*Deputy Manager for Operations*<br>*Space Station Freedom*<br>*Program and Operations* |
| 10:15 | Break | |
| 10:30 | Columbus Programme | Mr. Derek Dell<br>*ESA Representative*<br>*Space Station Freedom Program and Operations* |
| 11:00 | Japanese Experiment Module | Mr. Kazuhiko Yoneyama<br>*Director, Space Station Group*<br>*Space Station Program Department NASDA* |
| 11:30 | Canadian Space Station Program | Mr. Karl Doetsch<br>*Director General, Space Station Program*<br>*Canadian Space Agency* |
| 12:00 - 1:30 | Lunch | |

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| 1:30 - 5:30 | PLENARY SESSION 2 — FUTURE SPACE PROGRAMS AND PLANS<br>Session Chair: Mr. Lewis L. Peach<br>*NASA Headquarters* | |
| 1:30 | Space Station Freedom Evolution | Dr. Earle K. Huckins III<br>*Director, Space Station Engineering*<br>*NASA, Office of Space Flight* |
| 2:00 | SEI: An Update | Mr. Lewis Peach<br>Assistant *Director for Space Exploration,*<br>*NASA Office of Aeronautics, Exploration and Technology* |
| 2:30 | Advanced Space Transportation Systems | Mr. Robert Davies<br>*Chief, Advanced Transportation Planning*<br>*NASA, Office of Space Flight* |
| 3:15 | National Aero-space Plane | Dr. H. Lee Beach, Jr.<br>*Director for National Aero-Space Plane,*<br>*NASA Office of Aeronautics, Exploration and Technology* |
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**Tuesday August 6, 1991** *(continued)*

PLENARY SESSION 3 – FUTURE UTILIZATION OF SPACE STATION FREEDOM
Session Chair: Dr. John-David Bartoe
*NASA Headquarters*

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| 4:00 | Commercial Opportunities During Space Station Freedom Evolution | Mr. Richard Ott<br>*Director, Commercial Development Division*<br>*Office of Commercial Programs* |
| 4:30 | Technology Development on the Evolution Space Station | Dr. Judith Ambrus<br>*Assistant Director for Large Space Systems*<br>*NASA Office of Aeronautics, Exploration and Technology* |
| 5:00 | Expanded Research and Development on Space Station Freedom | Dr. Edmond M. Reeves<br>*Deputy Director, Flight Systems Division*<br>*NASA Office of Space Science and Applications* |

**Wednesday August 7, 1991**

8:00 - 11:45

STRATEGIES FOR EVOLUTION
Session Chair: Mr. W. Ray Hook
*NASA Langley Research Center*

| | | |
|---|---|---|
| 8:00 | A Historical Perspective on Space Station | Mr. W. Ray Hook<br>*Director for Space,*<br>*NASA Langley Research Center* |
| 8:30 | MIR: A Case Study for Evolution | Dr. B. J. Bluth<br>*Technical Assistant to the Deputy Director, Space Station Freedom Program and Operations* |
| 9:30 | Break | |
| 9:45 | Space Station Advanced Studies | Mr. Peter Ahlf<br>*Manager, Advanced Studies,*<br>*NASA Space Station Engineering*<br>*NASA, Office of Space Flight* |
| 10:15 | Space Station Advanced Development | Mr. Alan Fernquist<br>*Manager, Advanced Development*<br>*NASA Space Station Engineering*<br>*NASA, Office of Space Flight* |
| 10:45 | Commercial Aspects of Space Station Freedom | Mr. Kevin Barquinero<br>*External Programs Manager,*<br>*NASA Space Station Engineering*<br>*NASA, Office of Space Flight* |

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| **Wednesday** | **August 7, 1991** *(continued)* | |
| 11:15 | Evolution Design Requirements and Design Strategy | Mr. Donald Monell<br>*Space Station Freedom Office,*<br>*NASA Langley Research Center* |
| 11:45 | Lunch | |
| 1:30 - 4:45 | PARALLEL SESSION: EVOLUTION CONCEPTS AND OPERATIONS<br>Session Chair: Ms. Karen Brender<br>*NASA Langley Research Center* | |
| 1:30 | Baseline Operations Concept | Mr. Granville Paules<br>*Space Station Operations and Utilization*<br>*NASA, Office of Space Flight* |
| 2:00 | Astronaut Scientific Associate | Mr. Silvano Colombano and Michael Compton<br>*NASA Ames Research Center* |
| 2:30 | Growth User Requirements for Space Station Evolution | Mr. Kevin Leath<br>*McDonnell Douglas Space Systems Co.,*<br>*Washington SE & I* |
| 3:00 | Break | |
| 3:15 | SSF Growth Concepts & Configurations | Mr. William Cirillo<br>*Space Station Freedom Office,*<br>*NASA Langley Research Center* |
| 3:45 | STV Fueling Options | Mr. Kenneth Flemming<br>*McDonnell Douglas Space Systems Co.,*<br>*Kennedy Space Division* |
| 4:15 | A Safety Analysis of Cryogenic Propellant Handling on SSF | Mr. Sam Dominick<br>*Martin Marietta*<br>*Astronautics Group* |
| 1:30 - 4:30 | PARALLEL SESSION: SPACE STATION DATA SYSTEMS<br>Session Chair: Mr. Edward Chevers<br>*NASA Ames Research Center* | |
| 1:30 | Advanced DMS Architectures | Mr. Ed Chevers<br>*NASA Ames Research Center* |
| 2:15 | Optical Protocols for Advanced Spacecraft Networks | Dr. Larry Bergman<br>*NASA Jet Propulsion Laboratory* |
| 2:45 | Break | |
| 3:00 | Advanced Portable Crew Support Computer | Ms. Debra Muratore<br>*NASA Johnson Space Center* |
| 3:30 | ISE Advanced Technology | Mr. Barry R Fox<br>*NASA Johnson Space Center* |

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**Wednesday August 7, 1991** *(continued)*

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| 4:00 | Real-Time Data Systems | Mr. Troy Heindel<br>*NASA Johnson Space Center* |
| 4:30 | Computer System Evolution Requirements for Autonomous Checkout of Exploration Vehicles | Mr. Mike Sklar<br>*McDonnell Douglas Space Systems Company*<br>*Kennedy Space Division* |

**Thursday August 8, 1991**

8:00 - 11:45 PARALLEL SESSION: DISTRIBUTED SYSTEMS
Session Chair: Mr. Gregory Swietek
*NASA Headquarters*

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| 8:00 | Advanced Photovoltaic Power Generation | Mr. Edward Fisher<br>*Boeing Defense and Space Group*<br>*Huntsville, Alabama* |
| 8:25 | Advanced Solar Dynamic Power Systems | Mr. Michael Zernic<br>*NASA Lewis Research Center* |
| 8:45 | Power Management and Distribution Evolution | Mr. Michael Zernic<br>*NASA Lewis Research Center* |
| 9:05 | Solar Alpha Rotary Joint Capability Enhancement | Mr. David Snyder<br>*Lockheed Missiles and Space Company* |
| 9:30 | Power Management and Control Automation | Mr. James Dolce<br>*NASA Lewis Research Center* |
| 10:00 | Power Management and Distribution Automation | Mr. Louis Lollar<br>*NASA Marshall Space Flight Center* |
| 10:30 | Break | |
| 10:45 | Active Thermal Control System Evolution | Ms. Patricia Petete<br>*NASA Johnson Space Center* |
| 11:15 | Thermal Control System Automation | Mr. Roger Boyer<br>*McDonnell Douglas Space Systems Company* |
| 11:45 | Lunch | |

8:30 - 11:45 PARALLEL SESSION: ENGINEERING TOOLS AND TECHNIQUES
Session Chair: Mr. Mark Gersh
*NASA Headquarters*

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|---|---|---|
| 8:30 | Failure Environment Analysis Tool | Mr. Dennis Lawler<br>*NASA Johnson Space Center* |
| 9:00 | Space Station Freedom Software Reconfiguration | Mr. Larry Grissom and Bryan Porcher<br>*NASA Johnson Space Center* |

| Time | Topic | Presenter |
|---|---|---|
| **Thursday August 8, 1991** *(continued)* | | |
| 9:30 | Software Life Cycle Methodologies & Environments | Mr. Ernie Fridge<br>*NASA Johnson Space Center* |
| 10:30 | Break | |
| 10:45 | Intelligent Computer-Aided Training | Mr. Bowen Loftin<br>*NASA Johnson Space Center* |
| 11:15 | Knowledge Based Systems Scheduler Re-Host | Ms. Lynne Cooper<br>*NASA Jet Propulsion Laboratory* |
| 11:45 | Lunch | |
| 1:00 - 3:00 | PARALLEL SESSION: DISTRIBUTED SYSTEMS<br>Session Chair: Mr. Gregory Swietek<br>*NASA Headquarters* | |
| 1:00 | EMU System Evolution | Mr. Michael Rouen<br>*NASA Johnson Space Center* |
| 1:30 | ECLSS Evolution Analysis | Mr. Sandy Montgomery<br>*NASA Marshall Space Flight Center* |
| 2:00 | Environmental Control and Life Support System Automation | Mr. Brandon Dewberry<br>*NASA Marshall Space Flight Center* |
| 2:30 | Environmental Control and Life Support System Predictive Monitoring | Dr. Richard Doyle<br>*NASA Jet Propulsion Laboratory* |
| 1:00 - 3:00 | PARALLEL SESSION: TELEROBOTIC SYSTEMS<br>Session Chair: Mr. Alan Fernquist<br>*NASA Headquarters* | |
| 1:00 | Telerobotic System Technology | Mr. Wayne Zimmerman, Mr. Paul Backes<br>*NASA Jet Propulsion Laboratory* |
| 1:30 | Telerobotics Ground Remote Operation | Mr. Wayne Zimmerman, Mr. Bruce Bon<br>*NASA Jet Propulsion Laboratory* |
| 2:00 | Collision Avoidance Sensor Skin | Mr. John Vranish<br>*NASA Goddard Space Flight Center* |
| 2:30 | Mars Aerobrake Assembly | Mr. John Garvey<br>*McDonnell Douglas Space Systems Co. Advanced Product Development and Technology Division* |

FREEDOM

OPERATIONS AND
UTILIZATION
DIVISION

# Space Station Freedom Baseline Operations Concept

Presentation to the Evolution Symposium
6-8 August 1991


Granville Paules
Space Station Freedom Program
Operations Integration Branch
NASA Headquarters

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# FUNDAMENTAL MANNED BASE OPERATIONS REQUIREMENTS

OPERATIONS AND UTILIZATION DIVISION

- Assemble using the Shuttle
  - Assemble in components with each stage left in a safe configuration
  - EVA required (but minimized)

- Conduct Utilization at earliest practical opportunity during Assembly
  - Operate and utilize man-tended for several visits

- Permanently man when Assured Crew Return Capability exists
  - Initially four crew, growing to eight as program allows
  - Up to 180 day stay times

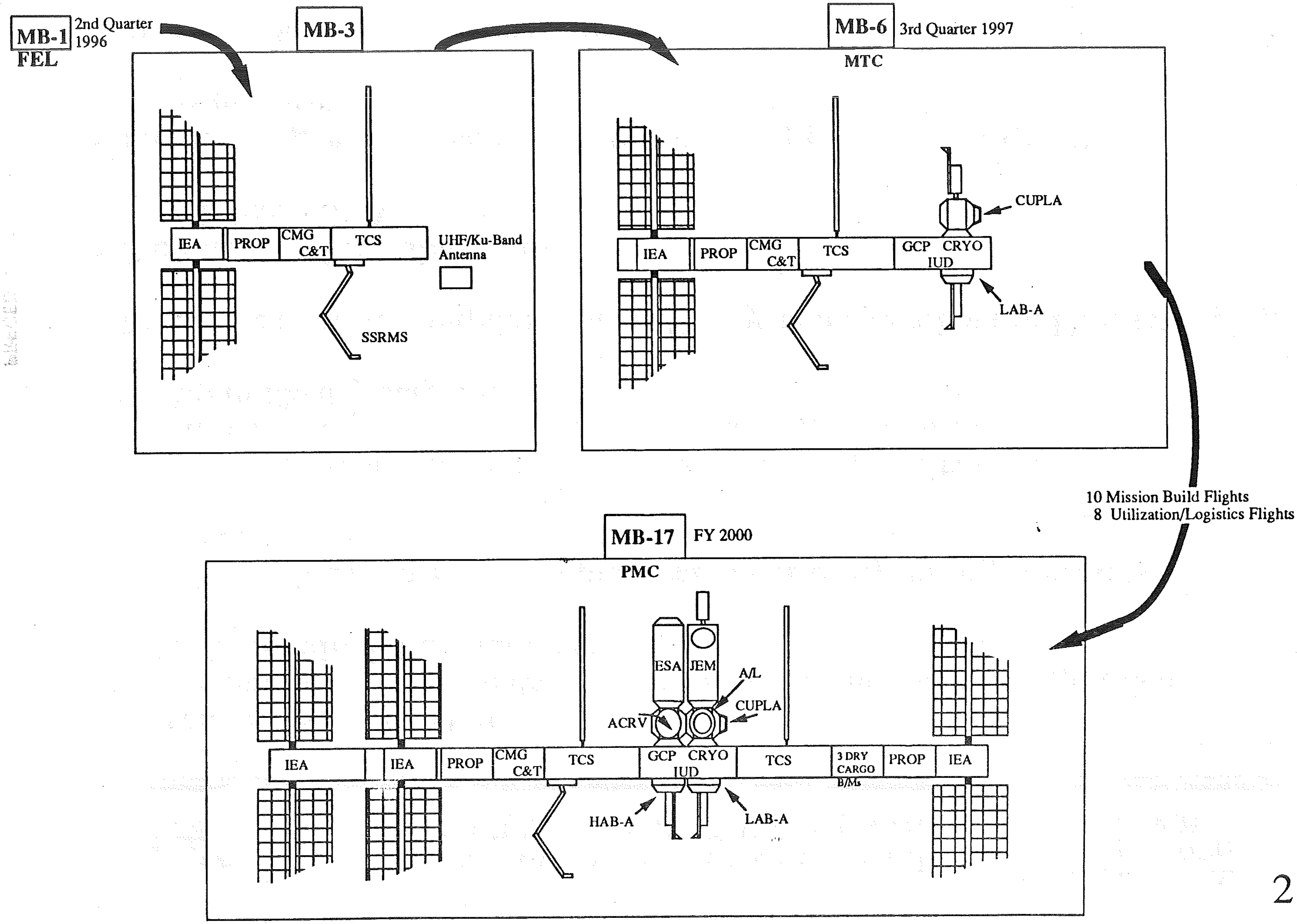
- Minimize crew time required for routine system operations and housekeeping

- Provide on-orbit maintenance
  - minimize EVA

- Provide long term logistics and utilization support with four Shuttle visits per year

- Plan for a 30 year operational-life

# Representative Assembly Configurations

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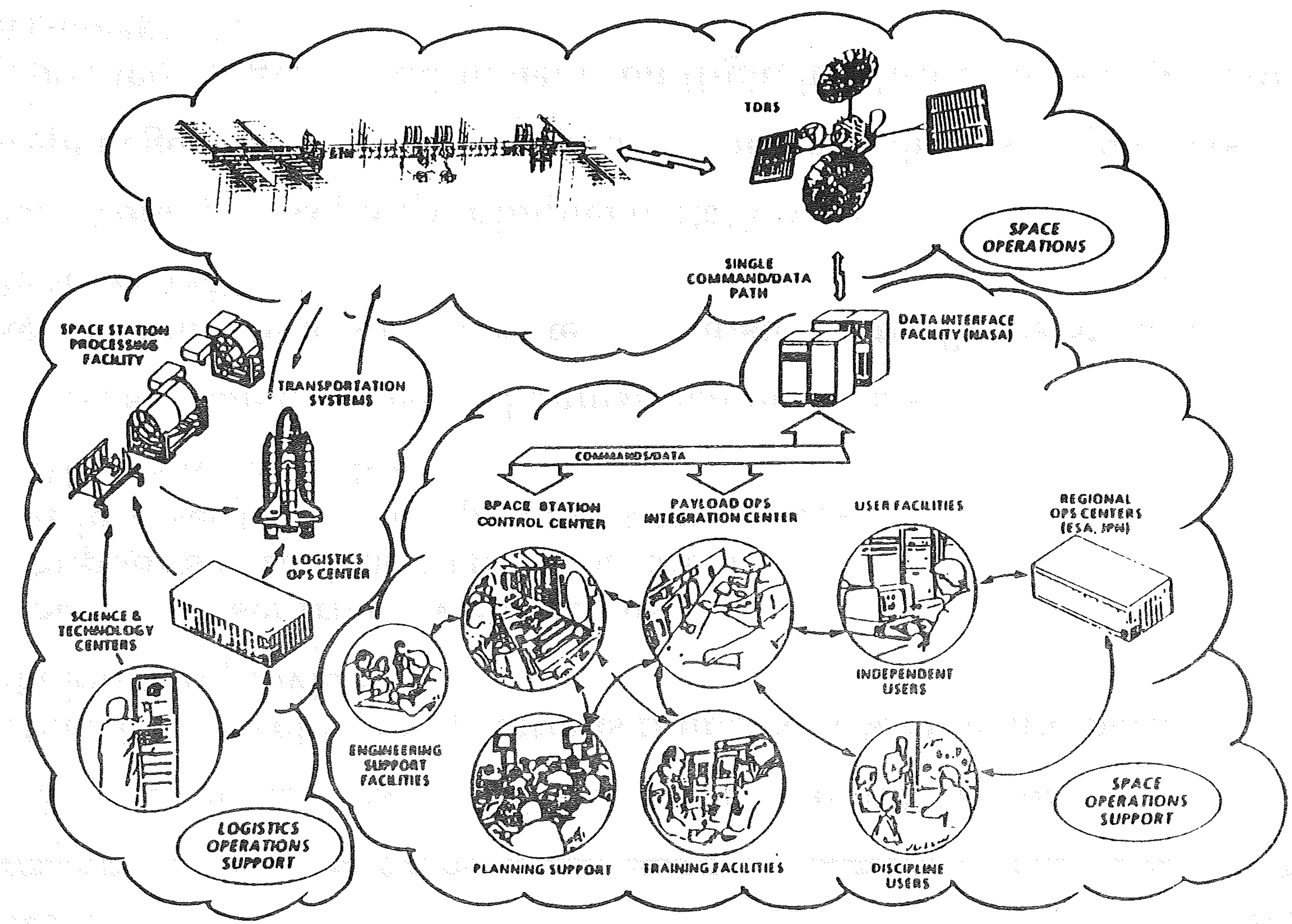
- Space Station Operations Task Force established in Fall 1986
  - -- Objective: Develop an operations framework for the international Space Station that provides:
    - Safe and user friendly operations
    - Supports participation of all partners
    - Addresses long-term operations cost issues
    - Allows for evolution
  - -- Expertise from manned and unmanned programs
  - -- Recommendations to Associate Administrator for Space Station in Summer 1987
  - -- Basic concept accepted for implementation
- Concept negotiated into Memoranda of Understanding with partners
- Documented Program requirements on flight hardware and software to meet concept
- Ground Systems Program Directive put ground infrastructure in place in May 1989

# MANNED BASE OPERATIONS INFRASTRUCTURE





- All partners provide flight hardware and supporting ground elements
  - -- Exchange of partner element user space for U.S. provided resources such as power
- All partners participate in management of station
  - -- Manned base operated as an integrated unit
  - -- Free-flying elements operated more autonomously
- All partners provide crew
- All partners share operating costs

# OPERATIONS MANAGEMENT

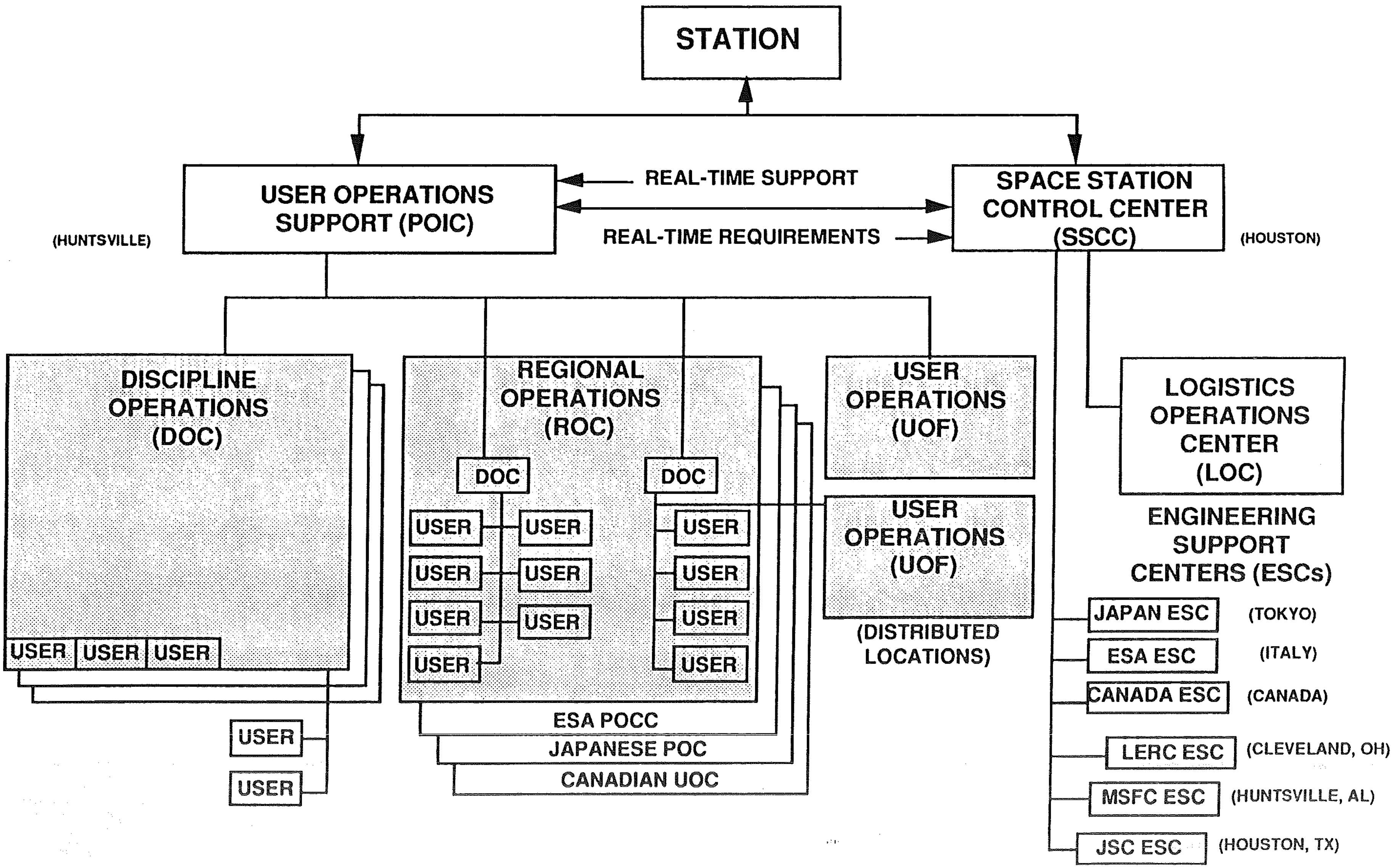
- Space Station Freedom is managed and operated as an integrated on-orbit facility
  -- Focused systems operations
  -- Focused integration of user operations
  -- Crew members work as team with assignments throughout Station

- Management and implementation is hierarchical
  -- Strategic (Policy) planning with 5-year horizon
    - Long term planning issues
  -- Tactical (Integration) planning with 2-year horizon
    - Coordination across functions and operations centers
  -- Execution planning and implementation
    - Detailed plans, real-time operations execution

# SPACE STATION OPERATIONS EXECUTION







## Space Operations

- All activities conducted on-board the Space Station Freedom manned base
  - Systems reconfiguration, monitoring, and control
  - Payload operations, monitoring, and control
  - On-board planning and replanning
  - Systems and payload maintenance and repair
  - Proximity operations
  - Communication with systems and payload controllers and users
  - Habitation activities

## Space Operations Support

- Systems planning, monitoring, and control by the Space Station Control Center (SSCC) at JSC

  - SSCC has prime responsibility for safety of the crew and integrity of the manned base

  - Supported by Engineering Support Centers (ESC) at all development sites

  - Systems training to be accomplished primarily at the Space Station Training Facility (SSTF) at JSC

    -- Additional training available at the international partner's training centers

  - Systems and payload activities integrated into common timelines

# Space Operations Support (cont.)

- User operations planning, monitoring, and control integrated at the Payload Operations Integration Center (POIC) at MSFC
  - Support to users located at user-developed operations centers, Discipline Operations Centers (DOC), Regional Operations Centers (ROC), and User Operations Facilities (UOF)
    - Flexible architecture to expand with the needs of the user community
  - User operations planning is distributed, then integrated by POIC
  - User decision-making body is the Investigator Working Group (IWG)
  - Support to user commanding is transparent to the user
    - Enable telescience while ensuring all commands are safe
  - Payload Training Center (PTC) at MSFC provides integrated payload training capability

## Logistics/Ground Operations Support

- Prime center of responsibility is KSC
  - Common logistics support for all programs at KSC being considered
- Space Station Processing Facility (SSPF) provides for physical integration:
  - Payloads-to-racks
  - Racks-to Logistics Modules
  - Logistics Modules and other flight hardware into Shuttle cargo elements
  - Logistics Module Maintenance
- Preflight integration of payload racks enabled at Payload Integration Center, domestic or international
- Logistics Support Analyses during DDT&E is basis for logistics requirements for spares, reliability, and maintenance
- Initial logistics operations support by the developer
  - KSC integrates resupply and sparing requirements
  - Logistics Operations Center at KSC after PMC
- Initial logistics information available via:
  - Distributed logistics databases at developer
  - Integrated Logistics Information Systems after PMC
- Logistics Module load planning using optimizing techniques

# Current Approach & Future Opportunities

| Management & Integration | Current Approach | Expert Systems/ Analytical Tools | Advance Information Systems |
|---|---|---|---|
| Program Management - Decision Support Systems | | | |
| Manifest Planning Systems | | | |
| Analytical Integration Support Tools (Systems & Payloads) | | | |
| Increment Plans Management - Decision Support Systems | | | |

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# Current Approach & Future Opportunities

OPERATIONS AND UTILIZATION DIVISION

## Space Operations

| | Current Approach | Expert Systems/ Analytical Tools | Telescience/ Teleoperations | Advance Info. & Communications Systems | Robotics |
|---|---|---|---|---|---|
| Space Systems Operations<br>- Systems Reconfiguration & Load Management<br>- Contingency Management<br>- Equipment Operation | | | | | |
| Payload Operations<br>- Experiment Execution<br>- Resource Allocation<br>- Conflict Resolution | | | | | |
| Maintenance Operations (EVA / IVA)<br>- Diagnostic and Maintenance Procedures<br>- Repair/Replace/Reverification | | | | | |
| Crew Health Care & Medical Operations | | | | | |
| Crew Workload Scheduling | | | | | |

FREEDOM

# Current Approach & Future Opportunities

OPERATIONS AND UTILIZATION DIVISION

| Space Operations Support | Current Approach | Expert Systems/ Analytical Tools | Telescience/ Teleoperations | Advance Info. & Comm. Systems | Robotics |
|---|---|---|---|---|---|
| Integrated Schedule Development<br>- Systems/Payloads/Resources | | | | | |
| Systems Performance Assessment & Diagnostic Support<br>- Sustaining Engineering | | | | | |
| Flight Software & Hardware Configuration Management | | | | | |
| Communication Systems Management<br>- Resource Allocation<br>- Scheduling | | | | | |
| Flight Techniques Development<br>- Training Techniques<br>- Training Equipment & Systems | | | | | |
| Trajectory Control | | | | | |
| Station/Shuttle Operations<br>- Proximity Operations Management<br>- Joint Activity Management | | | | | |

# Current Approach & Future Opportunities



| Logistics/Ground Operations Support | Current Approach | Expert Systems/ Analytical Tools | Advance Information & Communications Systems | Robotics |
|---|---|---|---|---|
| Transportation Services | | | | |
| Cargo Element Ground Processing<br>- Procedures<br>- Equipment | | | | |
| Payload Physical Integration | | | | |
| Prelaunch Acceptance Testing | | | | |
| Logistics Module Processing<br>- Load Planning/Module Reconfiguration<br>- Module Cleaning | | | | |
| Integrated Spares Inventory<br>- Stock Management | | | | |
| Ground Maintenance of Spares | | | | |

# SUMMARY

- The Baseline Operations Concept is designed to support the multiflight-multistage Assembly Sequence and the Post-PMC era

- Initial implementation of procedures and systems to support the concept are consistent with Shuttle and Spacelab experience

- Many opportunities exist to enhance the approaches initially being implemented

- Further insight during the Program's development phase and during early operations will help select and focus potential evolutionary paths

# "Facing Page Text" for the Astronaut Science Advisor Presentation at the Space Station Freedom Evolution Symposium August 7, 1991

Michael M. Compton
AI Research Branch
NASA Ames Research Center
(415) 604-6776

# "The Astronaut Science Advisor: Ground Testing During SLS-1"

The goal of the Astronaut Science Advisor (ASA) project is to improve the scientific return of experiments performed in space by providing astronaut experimenters with an "intelligent assistant" that encapsulates much of the domain- and experiment-related knowledge commanded by the PI on the ground. By using expert systems technology and the availability of flight-qualified personal computers, it is possible to encode the requisite knowledge and make it available to astronauts as they perform experiments in space. The system performs four major functions: diagnosis and troubleshooting of experiment apparatus, data collection, protocol management, and detection of interesting data.

The experiment used for development of the system measures human adaptation to weightlessness in the context of the neurovestibular system. This so-called "Rotating Dome" experiment (which was devised by Professor Laurence Young of MIT) was flown on the recent Spacelab Life Sciences One (SLS-1) Mission in June, 1991. This mission was used as an opportunity to test some of the system's functionality. Experiment data was downlinked from the orbiter, and the system then captured the data and analyzed it in real time. The system kept track of the time being used by the experiment, recognized occurrences of interesting data, summarized data statistically and generated potential new protocols that could be used to optimize the course of the experiment. The data collected during the mission is now being used to evaluate the system's advice and to fine-tune the system's performance in preparation for in-flight use of the system on SLS-2 in 1993.

The project was made possible by NASA grant NCC 2-570 and RTOP 506-47-11 for "Crew Station Design," respectively from the AI Research Branch and the Human Factors Division at NASA-Ames. Apple Corporation also provided generous support.

# Motivation

Perhaps the scarcest resource for manned flight experiments - on Spacelab or on the Space Station Freedom - will continue to be crew time. To maximize the efficiency of the crew, and to make use of their abilities to work as scientist collaborators as well as equipment operators, normally requires more training in a wide variety of disciplines than is practical.

In a typical laboratory setting the Principal Investigator (PI) is able to exert direct control over all aspects of an experiment, and his or her expertise can be brought to bear as events unfold, to correct problems or to follow new leads. This kind of flexibility is currently lacking during space experimentation, both due to time and resource constraints, and due to the physical distance from the PI at the time of the experiment. Communication is often not sufficient or not timely enough to bridge this physical gap.

Furthermore, astronauts are trained to perform a large number of experiments in different fields, and cannot be expected to acquire the in-depth knowledge required to deal effectively with all unexpected contingencies. This problem will be exacerbated in the Space Station era, with its longer tours and larger number of experiments.

# ASA Overview

The primary objective of the Astronaut Science Advisor project is to improve the scientific return of experiments that astronauts perform in space. The approach being pursued is to use expert systems technology and the availability of flight-qualified personal computers to encode the domain- and experiment-related knowledge and make it available to the astronauts in space-borne laboratories.

# Functions of the ASA

There are four main functions that the ASA performs:

- **Data acquisition:** The ASA can collect, reduce, and archive the raw experimental data that is generated during experimental sessions.
- **Data quality monitoring:** The ASA monitors the input data streams and checks for erratic or "pinned" signals, and other symptoms of poor data. If poor data is detected, the system notifies the astronauts that there may be equipment malfunctions and allows the operator to invoke the troubleshooting module.
- **Detection of "interesting data":** Data that is significantly different from what the Principal Investigator expects is noted and can be pursued in subsequent experimental runs.
- **Protocol management:** The ASA keeps track of the time allocated to the experiment and dynamically generates new protocols if the experiment is running ahead of or behind schedule, or if there is interesting data detected. This newly proposed experiment protocol can then be viewed by the astronaut operator who can then decide whether to adopt or decline the new protocol.

# Project Team

The ASA project team is comprised of individuals from several NASA centers and academic institutions.

At NASA's Ames Research Center, ASA project leader Silvano Colombano, Michael Compton, and Richard Frainier work in the Artificial Intelligence Research Branch. Irving Statler works in the Aerospace Human Factors Research Division.

Jurine Adolf and Tina Holden work at the Human Computer Interaction Laboratory at NASA's Johnson Space Center.

Team members from the Massachusetts Institute of Technology include Professor Laurence R. Young, a world-renowned space scientist who has devised numerous experiments for space-borne laboratories. Dr. Young, whose domain- and experiment knowledge is being modeled in the ASA, is also Director of the Man-Vehicle Laboratory at MIT. Working with Dr. Young at MIT are Nicolas Groleau (a graduate student) and Peter Szolovits of the MIT Computer Science Department.

# System Architecture

The ASA system is comprised of six modules:

- The **Data Acquisition Module** (DAM) collects and reduces the raw data from the on-board experiment equipment.
- The **Data Quality Monitor** (DQM) ensures that the incoming data is reliable and error-free.
- The **Protocol Manager** (PM) helps keep the experiment on schedule by monitoring the experiment's progress and suggesting modifications to the protocol when necessary.
- The **Interesting Data Filter** (IDF) recognizes experimental data that is likely to be "interesting" to the PI, and helps the protocol manager suggest ways to pursue the interesting results.
- The **Diagnostic and Troubleshooting Module** (DTM) helps the astronaut isolate, diagnose, and correct problems in the experimental apparatus.
- The **Executive Module** moderates all inter-module communications, and ensures proper and timely allocation of system resources.

These modules are distributed between two computers. The "Data Computer" runs the DAM and DQM, and is connected directly to the on-board experiment computer via an analog-to-digital converter. The back-end "AI Computer" runs the PM, IDF, DTM, and the Executive, and interfaces directly with the astronaut operator running the experiment.

# The Rotating Dome Experiment

The experiment used for development of the system measures human adaptation to weightlessness in the context of the neurovestibular system. This so-called "Rotating Dome" experiment was devised by Professor Young and has flown on two previous Spacelab missions (including, of course, the recent SLS-1 Mission in June, 1991). It is also scheduled for flight aboard SLS-2 in May, 1993.

The experiment apparatus consists of a hatbox-shaped dome the inside of which is covered with multi-colored dots. The subject inserts his or her head into the dome while the dome rotates in various directions and at various speeds. Shortly after the dome begins rotating, subjects cease to perceive that the dome is rotating and begin to sense that it is they themselves who are rotating in the opposite direction. This perceived self-rotation is called *vection*, and is recorded via a "joystick" which can be rotated by the subject to indicate the direction and magnitude of the vection. This joystick signal, along with signals from a torque sensor on a biteboard in the dome and electrodes on the subject's neck, constitute the raw data that is collected during the experiment.

There are three experimental conditions that are tested during the in-flight dome sessions. In the so-called *free-float* condition, the only objects in contact with the subject's body are the biteboard inside the dome and the joystick used to indicate vection. In the *neck-twist* condition, the subject is in free-float but starts with his or her neck bent at a forty-five degree angle relative to their body. In the *bungee* condition, the subject is held down against a floorplate by a shoulder harness to simulate the tactile cues on the soles of the subject's feet that occur in 1G.

## Setting up the Dome in the Spacelab Mockup

In this picture, the M.I.T. PI team is checking the procedure for setting up the Rotating Dome in the Spacelab mockup at JSC. This mockup was used during the astronauts' training.

# Testing the Dome in the Spacelab Mockup

This picture shows one of Professor Young's co-investigators testing the Dome apparatus after setup it up in the Spacelab mockup at JSC.

# Astronauts Conducting the Dome Experiment On-Orbit

This picture shows a frame of the split-screen video that was downlinked from the Spacelab during the Rotating Dome session on Mission Day 5. The image on the right side of the picture is a rear view of one of the astronauts performing the experiment (the astronaut's head can be seen in the dome with her shoulders and torso extending to the lower-right corner). The image on the left side of the picture is a closeup of the subject's eye taken from the video camera inside the dome.

# Typical Experiment Session

A typical session for the Rotating Dome experiment lasts approximately one hour, and consists of setup and calibration steps, approximately six data collection runs, followed by shutdown and stowage steps .

During setup, the astronauts deploy the apparatus, connect the dome and other sensors to the experiment computer, and test the equipment to make sure that everything is working properly.

The actual experiment runs each consist of six thirty-second trials during which the dome rotates and data is collected. During each trial, the dome rotates at a certain speed (thirty, forty-five, or sixty degrees per second) either clockwise or counter-clockwise. Each run tests one of the experimental conditions (free-float, neck-twist, or bungee, as described before). Some of the runs, therefore, include additional steps such as attaching or adjusting the bungee harness.

After data collection is complete, the astronauts then shut down the experiment and disassemble and stow the apparatus (although sometimes the dome is left deployed if it is going to be used later in the mission).

# Hypothetical ASA Scenario

To illustrate the usefulness of the ASA to astronauts in flight, consider the following hypothetical scenario:

The second Rotating Dome session is being performed approximately mid-way through a mission. The session, which involves data collection from two subjects, is running slightly behind schedule. During the first Dome session on the previous day, the first subject exhibited interesting data. The second subject also participated in the previous session, yet exhibited erratic data.

How should the current experiment protocol be refined to maximize the scientific return from this Dome session?

# The "Proposed" Protocol

Here is a screen from the Protocol Manager that shows how ASA might respond in the scenario just described.

On the left part of the screen is the original protocol, showing the predefined sequence of subjects, runs and conditions to be carried out during this session. This display indicates that the first subject is currently performing a neck-twist run.

On the right part of the screen is the new protocol being proposed by the ASA in response to the fact that the session is a little behind schedule and the subjects' previous performance. Note that the ASA suggested that the second subject's bungee run be replaced by an additional run involving the first subject in the free-float condition. This recommendation is made in light of the fact that the first subject provided interesting data the day before, while the second subject's previous data had been erratic. Also, substituting a free-float run for a bungee run saves approximately two minutes of bungee-setup time, which will help to put the session back on schedule.

# Diagnosis and Troubleshooting Example

Another important capability provided by ASA is the ability to help astronauts identify and correct malfunctions with the equipment apparatus. The following is another hypothetical example of how the ASA might help an astronaut fix a problem with one of the electrodes used in the Rotating Dome experiment.

Suppose that while preparing a new subject for a Dome run, one of the electrodes designed to record neck-muscle activity malfunctions. Without the ASA, the problem would probably not be noticed by the astronaut operator (because the electrodes are generally only tested while setting up the experiment apparatus initially). As a result, the bad electrode might only be recognized by the Principal Investigator on the ground when the "flat" signal began to print out on the stripchart recorder in the SMA. (Note that if this particular session happened to take place during the period of time when the Spacelab was out of of communication with the ground, the problem might not be detected until the data is downloaded that night, well after the experiment session has ended!) Assuming the PIs on the ground noticed the problem and were able to isolate it, they would probably need to request air-to-ground communications and convey a diagnosis and recovery procedure up to the crew (which might take up a substantial portion of the time remaining for the experiment itself).

If the ASA were being used by the crew on board, it would recognize the bad signal during the first experimental trial and automatically notify the operator that a signal was bad. The diagnosis module would then estimate how long it might take to fix the problem and then either recommend a diagnosis procedure (such as swapping amplifiers with the other electrode) or recommend that the experiment session continue without the signal. In either case, the proper advice and help would be available to the crew immediately, regardless of whether or not the orbiter was in contact with the ground.

## Support of the SLS-1 Mission

The ASA was used in support of the Rotating Dome experiment during three major phases of the Spacelab Life Sciences One mission.

During pre-flight data collection at the Baseline Data Collection Facility at JSC, the system was used to help collect data at launch-minus-150 days, launch-minus-75 days, launch-minus-45 days, launch-minus-30 days, and launch-minus-15 days. These data, which represent how the subjects perform under normal conditions in 1G, served as a baseline against which to compare the data collected in subsequent in-flight and post-flight sessions.

During the actual mission, the Rotating Dome experiment was carried out on Mission Day 5 and Mission Day 6. During these experiment sessions, the ASA system was used on the ground near the Science Monitoring Area (SMA) at JSC. The ASA was connected to the same stream of raw data that was downlinked from the Spacelab and monitored by the PIs inside the SMA.

After the mission, the ASA was used to collect post-flight data at NASA's Dryden Flight Research Facility at Edwards AFB, CA. These data collection sessions, which took place on return-plus-0 days, return-plus 1 day, return-plus-2 days, return-plus-4 days, return-plus 7 days, and return-plus-10 days, measured the astronauts' responses as they re-adapted to gravity.

## Monitoring the Dome Experiment in the SMA

This picture shows the Principal Investigators for the Rotating Dome experiment monitoring its progress during Mission Day 5. The PIs utilize a stripchart recorder and air-to-ground communications (when available) to help the astronauts as they conduct the experiment on orbit.

# Operating the ASA During the On-Orbit Dome Experiment

In the conference room outside the SMA, the ASA system monitored, in real-time, the data coming down from the orbiter. The computer on the right is the so-called "AI Computer" on which the reasoning components of the ASA reside. The computer in the middle is the so-called "Data Computer" that actually collects, checks, and archives the raw data before sending the reduced data over to the AI Computer. The portable computer on the left was also hooked up to the downlinked data, and monitored the digital data stream and reflected the status of the experimental apparatus.

## Accomplishments

The primary accomplishment of the ASA system in its testing during SLS-1 was that it proved that the system works under realistic conditions.

The data collection and quality monitoring modules correctly acquired and interpreted the data, and were able to keep up with the real-time data stream.

The data analysis routines correctly interpreted the data and provided meaningful quick-look analyses and statistical summaries of the experiment data that were printed out and taken in to the PIs in the Science Monitoring Area, who generally agreed with the analyses.

The ASA generated new protocols that included steps to pursue the "interesting" data and that would make optimal use of the time remaining for the experiment. These new protocols were also printed out and taken into the SMA, where they were used by the PI team to plan for the possibility of subsequent experiment sessions.

# Lessons Learned

There were several major lessons learned during testing of the ASA:

- **Science experiments conducted in space should permit reactivity:**
  Pre-defined experimental protocols don't offer the astronauts enough flexibility to deal effectively with unexpected problems or opportunities. The limited availability of air-to-ground communication and the circuitous nature of the air-to-ground links can severely limit the ability of PIs on the ground to help the astronauts during experiments.

- **The ASA would have been useful to the crew in-flight:**
  The crew experience various equipment and scheduling problems (such as delayed session starts and deferred subjects). The ASA suggested protocol refinements that would have minimized the effect of these occurrences on the data collection.

- **Increased emphasis on set-up would have been useful:**
  Development of the ASA focussed primarily on the data collection aspects of the experiment. However, set-up and calibration are important parts of the protocol and need to be addressed more thoroughly by the ASA.

- **An in-flight system could avoid many of the limitations of a ground-based system:**
  The ASA, while running on the ground, was subject to the same limitations that affected the PIs influence on the experiment (especially loss-of-signal events and indirect communication with the crew). An in-flight system would have been able to avoid much of these problems.

## "Shuttle Science" vs SSF Science

There are significant differences between the nature of scientific experiments that are carried out on board the Space Shuttle and the way that future experiments are likely to be carried out aboard Space Station Freedom.

**Mission Duration:** On the Space Shuttle, missions are generally limited to a period of seven to ten days. On the other hand, astronauts aboard Space Station Freedom will conduct experiments that may span months or even years.

**Experiment Variety:** Relatively few experiments are performed on Space Shuttle missions. On SLS-1, which was the first Shuttle mission dedicated to life sciences experimentation, eighteen primary experiments were conducted, all of which were designed to study the affect of spaceflight on living creatures. The number and variety of experiments that are likely to be performed aboard Space Station, however, will be significantly greater, and may even increase by an order of magnitude over Shuttle experiments.

**Experiment Protocols:** Protocols that dictate how experiments are conducted aboard the Space Shuttle are worked out years in advanced of the mission, are very tightly scripted, and are very hard to refine or modify once the mission is underway. However, protocols for experiments to be performed on Space Station must be very flexible and adaptable to the initial results.

# Milestones

During 1990, the ASA team focused primarily on development, integration, and testing of the various software modules that comprise the ASA system.

Much of the effort during 1991 has focused on preparation for and support of the ASA testing that was performed in conjunction with the SLS-1 mission. This included the pre- and post-flight baseline data collection sessions as well as the collection of in-flight data during the mission itself.

For the remainder of 1991 and much of next year, the ASA team will be refining the system based on the experience gained during the SLS-1 mission, and preparing for the planned flight of the ASA on board SLS-2. This will involve rehosting the software on flight-qualified portable Macintosh computers, and preparation for training the SLS-2 crew on operation of the ASA. The project team is also investigating issues involved at generalization of the system and looking at other potential applications of the ASA to spaceborne science.

In 1993, the system is planned for use aboard SLS-2, and will also be used during the pre- and post-flight data collection sessions for that flight, which is currently scheduled for May, 1993.

# Potential Applications

Other space scientists have expressed interest in using the ASA for their experiments. These potential applications would serve as a means by which to help generalize the system and would result in a system that could be useful to a broader segment of the space science community.

These potential applications include:

- **The Vestibular Sled Experiment**: Another of Professor Young's experiments, the Vestibular Sled measures human adaptation to weightlessness from a slightly different perspective from the Rotating Dome. The Sled experiment is planned for flight on the second International Microgravity Laboratory mission (IML-2) in the 1995-96 time frame.
- **Modeling of Planetary Atmospheres**: An experiment devised by Tom Scattergood and Chris McKay involves studying the formation of organic aerosols in Titan's atmosphere by simulating that environment in the so-called Gas Grain Simulation Facility.
- **Cell Growth in the Weissman Apparatus**: This experiment, devised by William Weissman and Rose Grymes, explores how the growth of lymphocytes is affected by microgravity.
- **Biomedical Monitoring and Space Research Centrifuge**: These domains, being investigated by Robert Mah, would involve monitoring of astronaut physiology and conditioning , and control of experiments that use the Space Research Centrifuge.

# Conclusions: Implications for SSF

The experience gained during the testing of the ASA in the context of the SLS-1 mission has implications for how automation can help maximize the scientific return of experiments carried out aboard Space Station Freedom.

"Missions" aboard Space Station will be far longer than those currently possible aboard the Space Shuttle. These long-duration missions will permit a wider variety of experiments, which in combination with the smaller crews will limit the pre-flight training and ground support that will be available to astronauts who must perform experiments in the Space Station environment.

Experiments that will be carried out on board the Space Station are likely to be more reliant on the initial experimental results than on a pre-defined protocol. This will require that the astronauts be capable of interpretation of preliminary scientific data in order to determine the subsequent course of the experiments.

The best way to meet these needs of crew "reactivity" and reduced reliance on help from the ground is to use advanced automation techniques (such as ASA) to provide the crew with on-board assistance.

# The Astronaut Science Advisor: Ground Testing During SLS-1


Michael M. Compton

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Space Station Evolution Symposium

August 7, 1991


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# Motivation

**Time and resource constraints severely limit flexibility during space experimentation:**

- PI is physically distant from experiment.
- Communication is often of insufficient bandwidth or not timely enough.
- Experiments are numerous and varied.
- Space Station environment is likely to exacerbate the situation.



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# ASA Overview

- **Objective:**

  To improve the scientific return of experiments performed in space.

- **Approach:**

  Use expert systems technology to encode the domain and experiment knowledge commanded by the Principal Investigator and make it available to the astronaut experimenters.

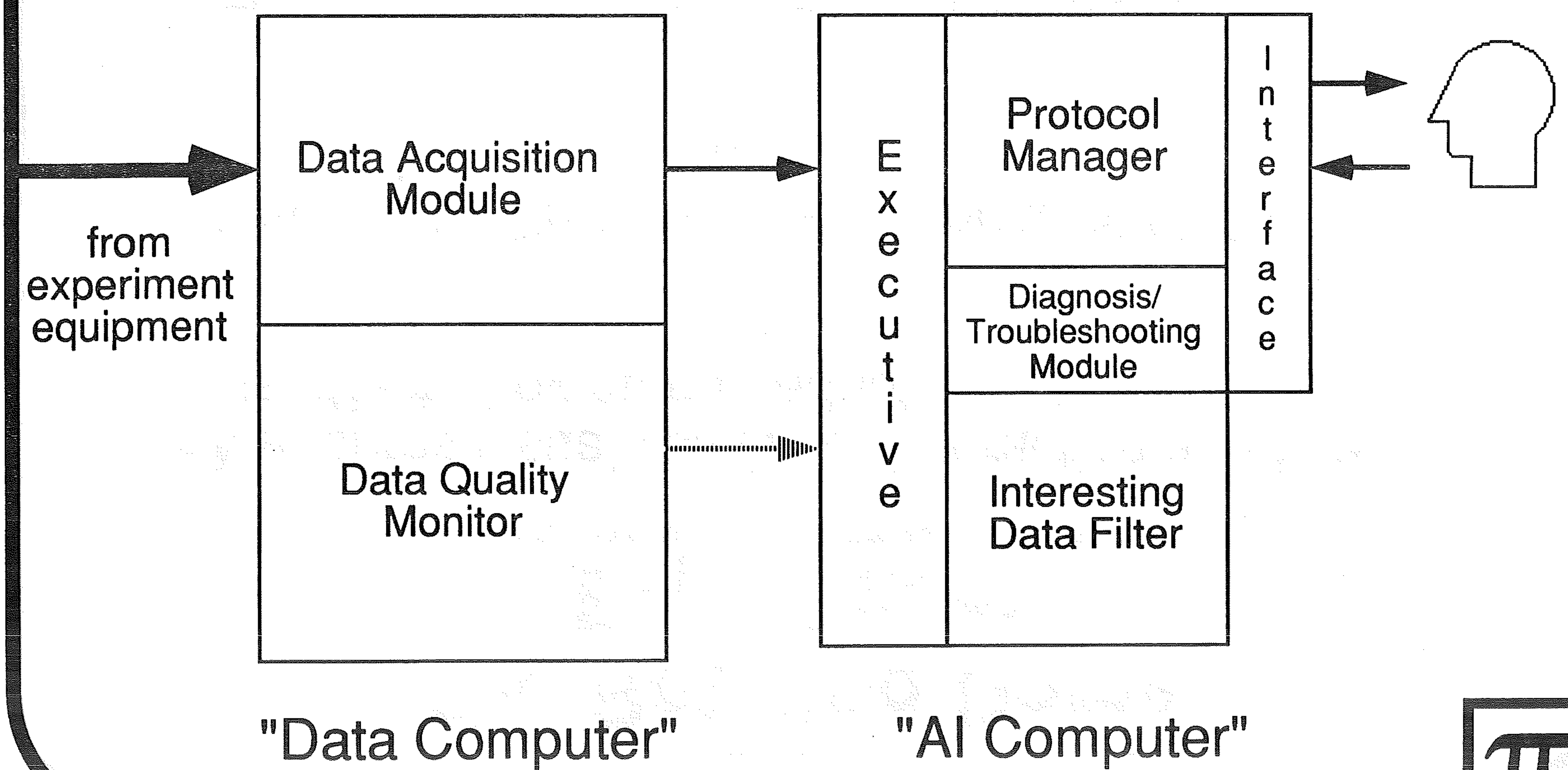
# Functions of the ASA

- Capture, reduce, and archive experimental data
- Monitor data quality and help diagnose problems with equipment when experimental data is erratic or poor
- Identify and permit investigation of "interesting" data
- Suggest protocol changes that would result in better utilization of remaining time

# Project Team

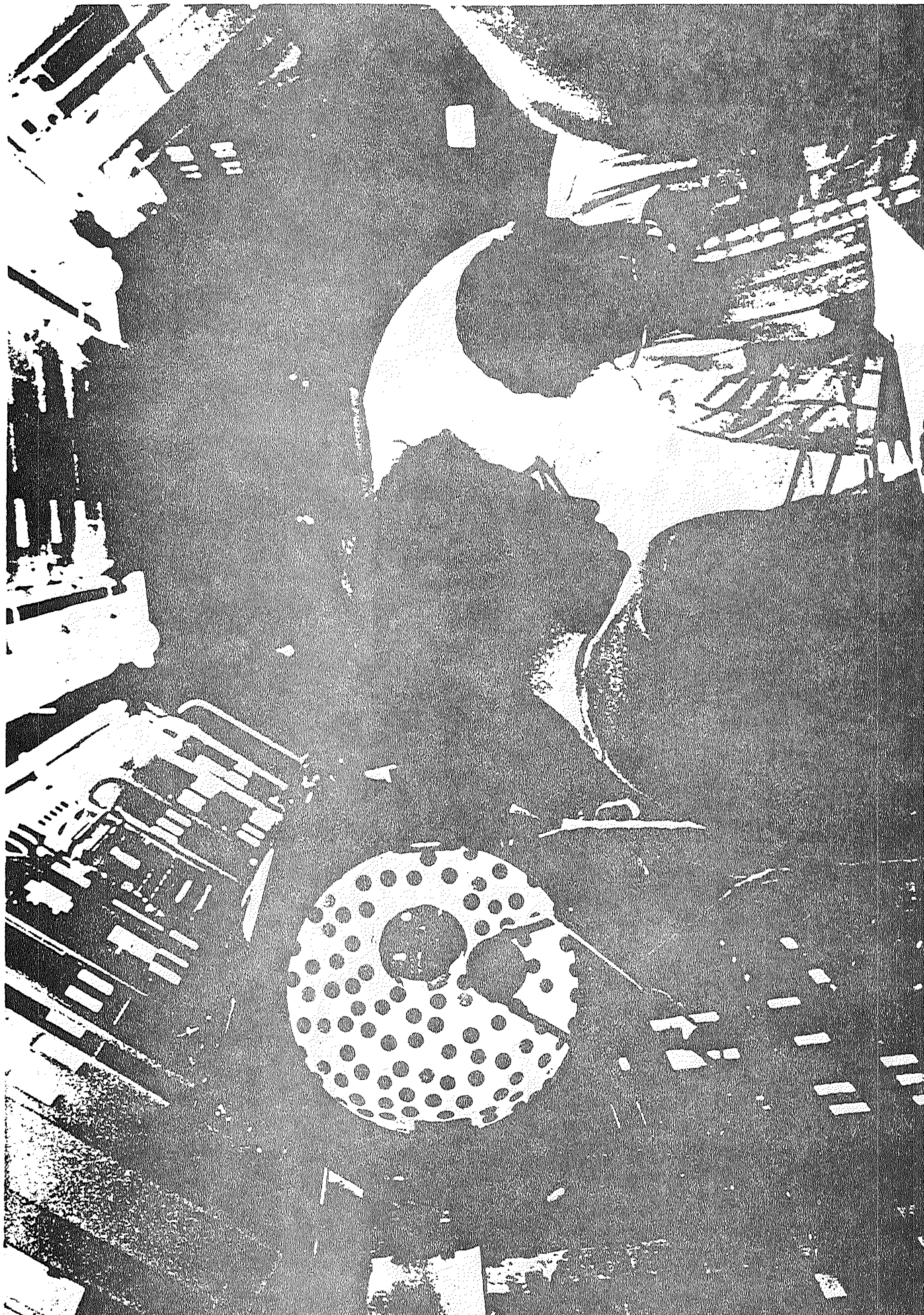
- **Ames Research Center**
  - Silvano Colombano
  - Richard Frainier
  - Michael Compton
  - Irving Statler
- **Johnson Space Center**
  - Jurine Adolf
  - Tina Holden
- **M.I.T.**
  - Prof. Laurence R. Young *(experiment PI)*
  - Nicolas Groleau
  - Peter Szolovits

# System Architecture



# The Rotating Dome Experiment

- Measures visual/vestibular interaction and how it is affected by human adaptation to microgravity
- Devised by Professor Larry Young of MIT's Man-Vehicle Laboratory
- Flown on two previous Spacelab missions (including SLS-1 in June, 1991)
- Scheduled for flight aboard SLS-2 (in May, 1993)



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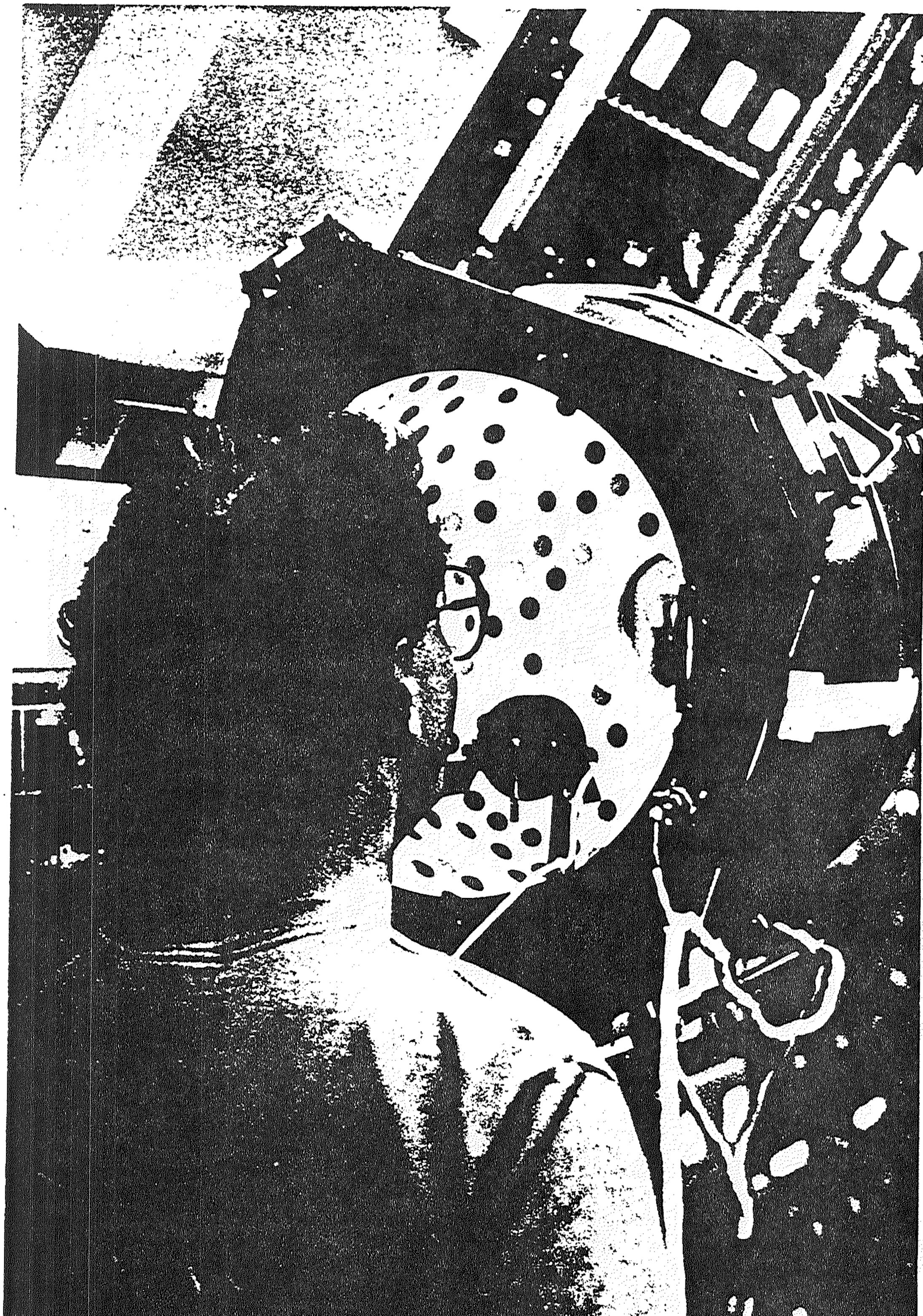
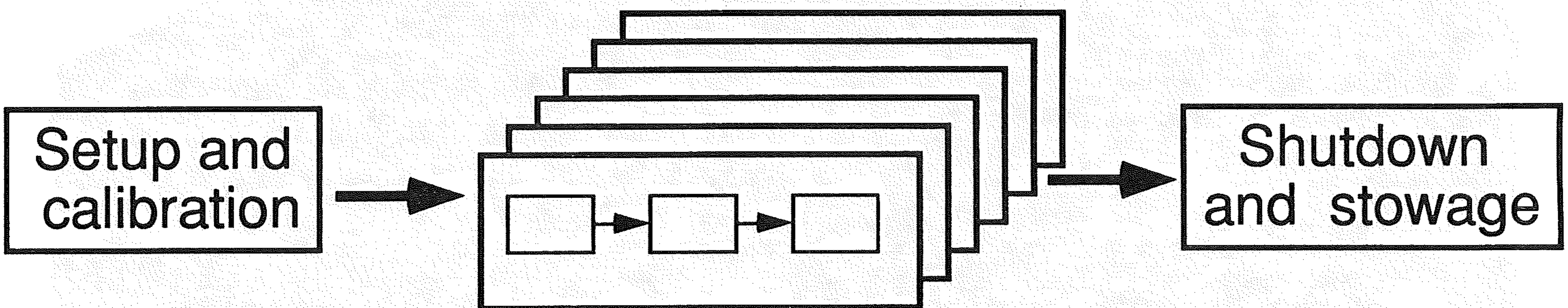


# Typical Experiment Session




Data collection

# Hypothetical ASA Scenario

- The dome experiment, with two subjects, is running slightly behind schedule.
- Subject 1 had exhibited "interesting data" on the previous day.
- Subject 2 had exhibited erratic data during the previous session that same day.

**How should the protocol be refined to maximize the scientific return of this session?**

π

# The "Proposed" Protocol

Options

minutes behind — minutes ahead

15 10 5 0 5 10 15

HELP Notes EXIT

| Current Protocol | | | | | | Proposed Protocol | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | run | 3 | MS2 | free-flt | 1 | 6 | run | 3 | MS2 | free-flt | 1 |
| 7 | run | 3 | MS2 | nck-twst | 1 | 7 | run | 3 | MS2 | nck-twst | 1 |
| -- | att-bung | 3 | MS2 | bungee | . | 7.1 | run | 3 | MS2 | free-flt | 1 in |
| 8 | run | 3 | MS2 | bungee | 1 | -- | att-bung | 3 | MS2 | bungee | . |
| -- | exit | 1 | . | bungee | . | 8 | run | 3 | MS2 | bungee | 1 |
| -- | adj-bung | 2 | . | bungee | . | -- | exit | 1 | . | bungee | . |
| -- | enter | 3 | PS1 | bungee | . | -- | det-bung | 2 | . | none | . |
| 9 | run | 3 | PS1 | bungee | 1 | -- | enter | 2 | PS1 | none | . out |
| -- | det-bung | 2 | PS1 | none | . | 10 | run | 3 | PS1 | free-flt | 1 |

MET 03/14:07:00 GMT 15:21

# Diagnosis and Troubleshooting Example

- During setup for a new subject, one of the signals that convey neck muscle activity "goes flat".
- Without the ASA, the problem might go unnoticed until PIs on the ground recognize the problem, notify the astronauts (and perhaps convey a troubleshooting procedure).
- With the ASA, the system would immediately notice the bad signal and invoke the diagnosis and troubleshooting module and help the astronauts correct the problem (or recommend that the experiment proceed without that signal).

# Support of SLS-1 Mission

- **Pre-flight baseline data collection:**
  - system used to collect and analyze data from Rotating Dome experiment in the Baseline Data Collection Facility at JSC on L-150, L-75, L-45, L-30, and L-15 sessions

- **Ground support during flight experiment:**
  - system used in the Science Monitoring Area at JSC to collect and analyze in-flight data from the Dome experiment downlinked from Spacelab

- **Post-flight data collection:**
  - system used at Dryden to collect and analyze data from the Dome experiment on R+0, R+1, R+2, R+4, R+7, and R+10 sessions

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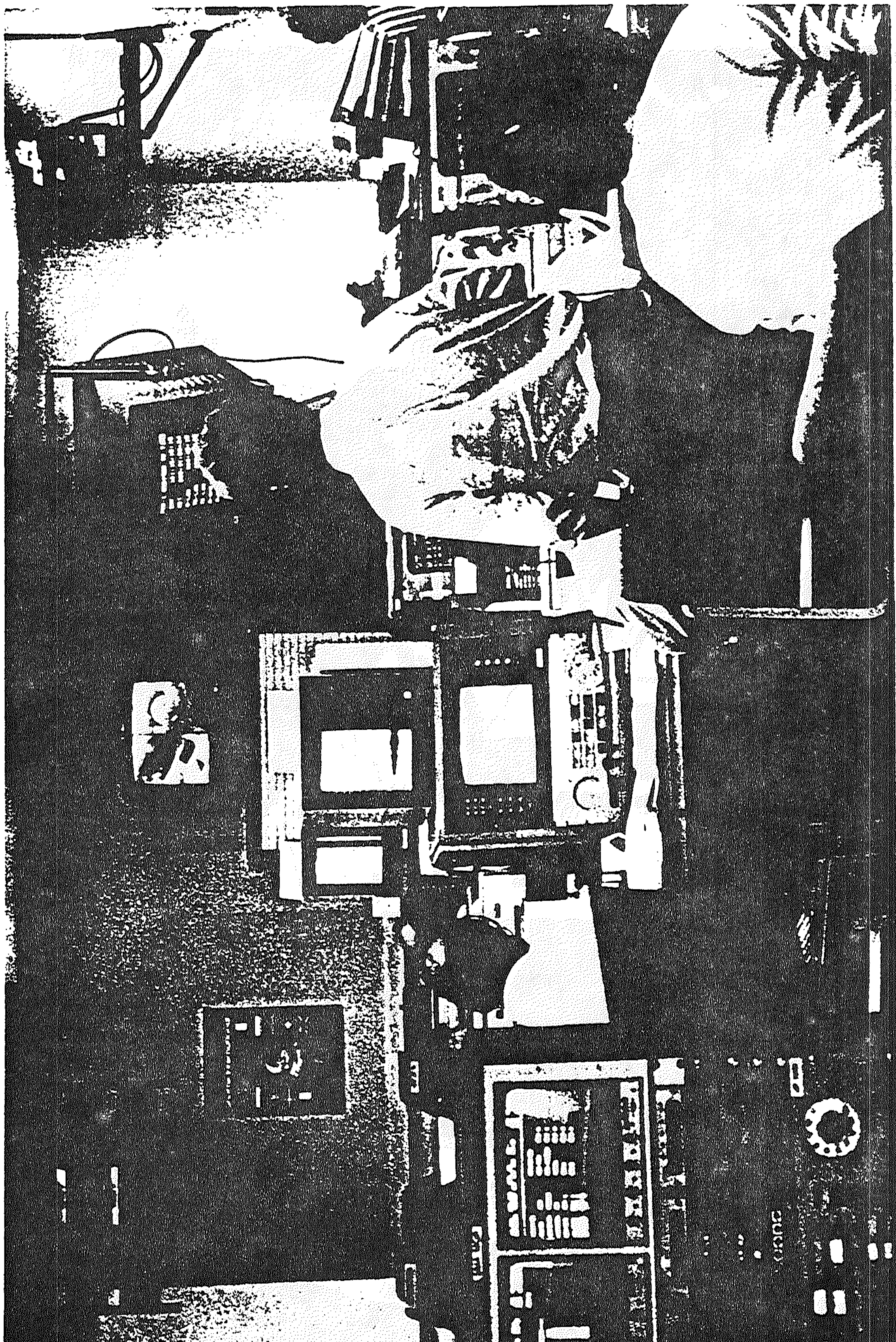

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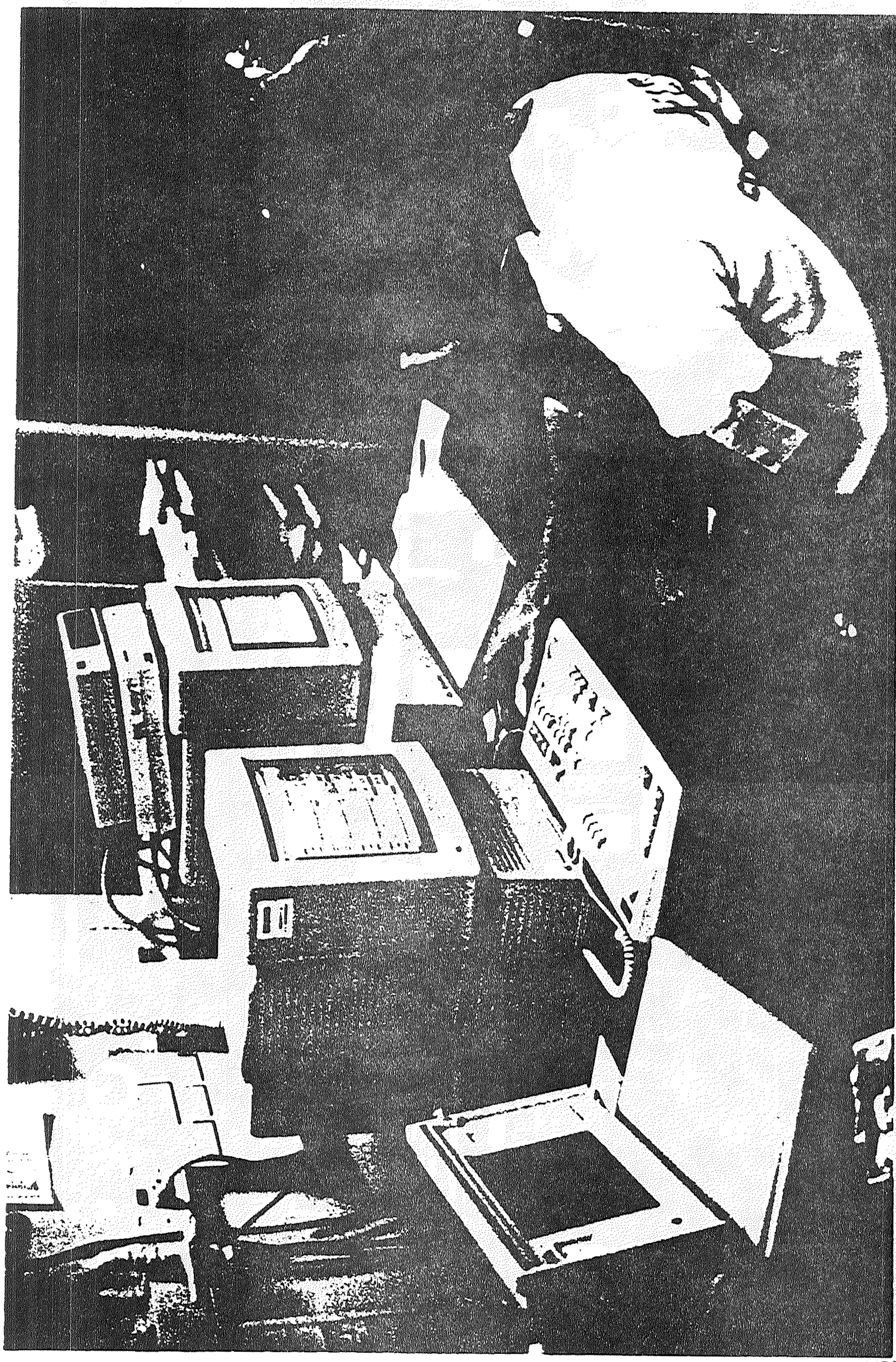

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# Accomplishments

**The system worked under realistic conditions.**

- Collection and archival of downloaded data
- Quick-look analysis and summary of data
- Generation of potential new protocols

# Lessons Learned

- Space science should permit reactivity to
  - cope with problems
  - pursue unexpected opportunities
- The ASA would have been very useful to crew in-flight (particularly for troubleshooting and replanning).
- Conduct of the experiment suggested an increased emphasis on experiment set-up would be useful.
- An in-flight system could avoid many of the limitations inherent in ground-based systems.

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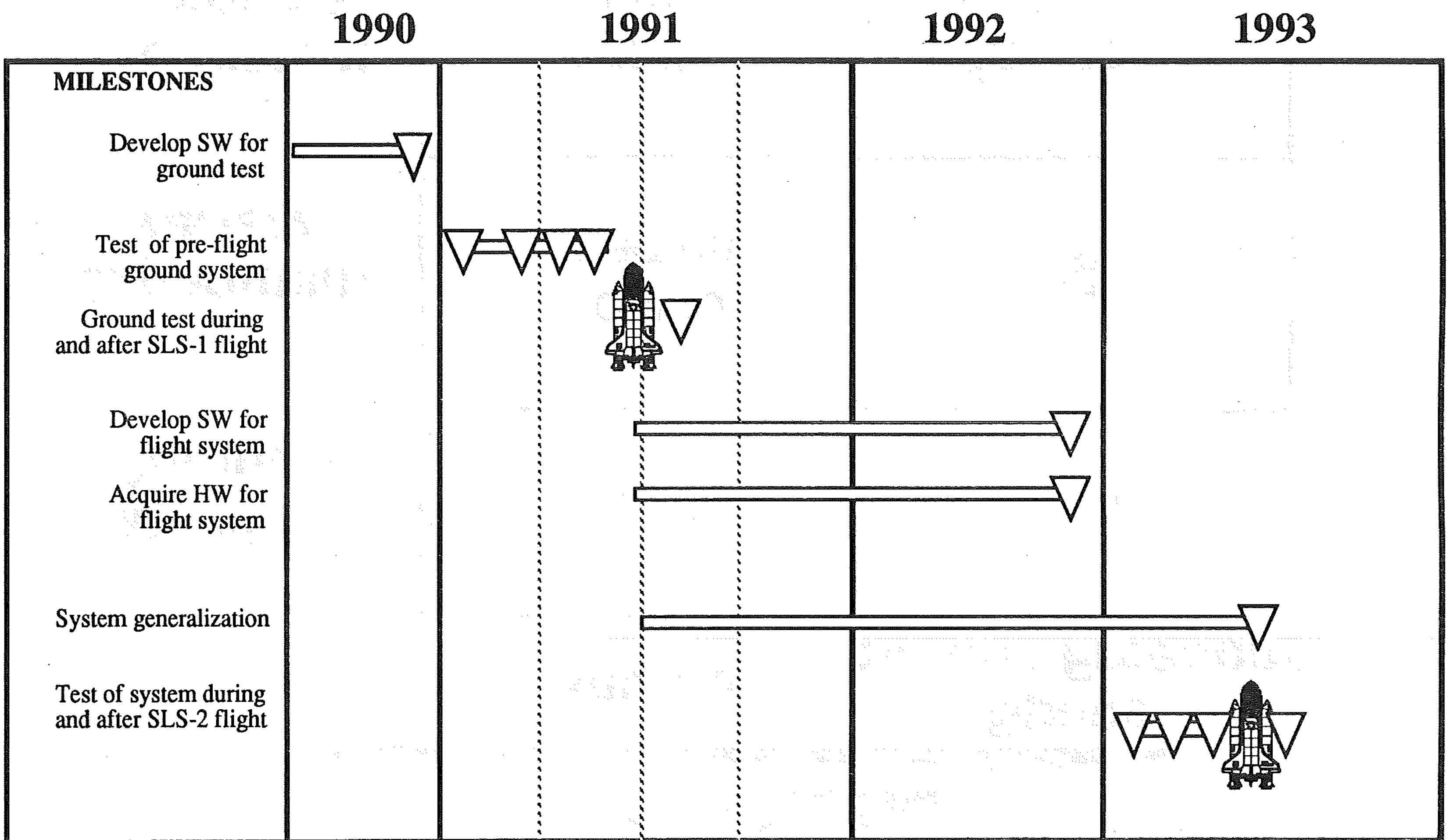
# "Shuttle Science" vs SSF Science

| | Shuttle | Space Station Freedom |
|---|---|---|
| **Mission Duration** | days | months |
| **Experiment Variety** | low to medium | high |
| **Experiment Protocols** | tightly scripted | adaptable to initial results |

# Milestones


1990
1991
1992
1993
MILESTONES
Develop SW for ground test
Test of pre-flight ground system
Ground test during and after SLS-1 flight
Develop SW for flight system
Acquire HW for flight system
System generalization
Test of system during and after SLS-2 flight

# Potential Applications

- The Vestibular Sled Experiment
- Simulation of Titan Atmosphere in Gas Grain Simulation Facility (GGSF)
- Cell Growth in Wiessman Apparatus
- Biomedical Monitoring and Space Research Centrifuge

# Conclusions: Implications for SSF

- Long-term "missions" aboard SSF will require a different approach to ground support of experiments
- Scientific return increases with reactivity
- Automation techniques can reduce reliance on ground

# Evolution User Requirements for the Restructured Space Station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**SPACE STATION EVOLUTION - BEYOND THE BASELINE**
**August 6 - 8, 1991**
**League City, Texas**

# Abstract

Space Station Freedom (SSF) is designed to be an Earth-orbiting multidisciplinary research and development (R&D) facility capable of evolving to accommodate a variety of potential uses. In order to identify SSF evolution requirements and define potential growth configurations, NASA Langley research Center's Space Station Freedom Office is analyzing user resource requirements for the post-PMC timeframe. The analysis goal is to define resource levels, including crew, power, and volume, which allow full utilization of SSF capabilities commensurate with minimum essential user requirements. Multiple scenarios have been studied including core R&D and combined SEI plus R&D utilization. This paper presents an analysis summary of a core R&D utilization scenario. Included are discussions of resource allocation assumptions for specific R&D disciplines, user requirements trends, and growth resource projections. These preliminary results show total resource requirements of thirteen crew, 150 kW power, and additional laboratory volume equivalent to a second U.S. laboratory module. Additionally, orthogonal growth structure was identified as required to support SSF systems and users.

# Discussion Topics

- **Utilization Drivers for Growth / Evolution**

- **Utilization Analysis Summary**

- **SSF Evolution Requirements - Core R&D Utilization**
  - Pressurized Volume
  - Crew
  - Power/Thermal
  - Structure

- **Summary and Conclusions**

# Discussion Topics

- Innovative Drivers for Growth / Profits
- Utilization / Analysis Summary
- [illegible] Requirements - [illegible] Utilization
  - Pressurized Volume
  - Crew
  - [illegible]
  - [illegible]
- [illegible]

## Utilization Drivers for Growth / Evolution

Through repeated analyses of user requirements for station resources, it has become apparent that the resources available to the users will need to be increased beyond those available at PMC. In fact, the accommodation of the PMC payload complement identified in the Level II flight-by-flight user payload and resupply cargo model requires sharing of crew and power, and falls short of meeting the volume requirements. In order to permit full operation of user payloads, as well as to accommodate a reasonable percentage of the number of experiments they wish manifested on station, it will be necessary to grow each of these resource capabilities. The preferred manner of growth is such that the available volume, crew, and power balance with user demand in such a way that no large surplus exists in any one resource.

In the course of providing additional user resources, the station will evolve to incorporate new functions for users as well as for station operations. As an example, several large external payloads have been defined by OSSA, but cannot be accommodated on the PMC pre-integrated truss (PIT). Some form of growth structure will, therefore, be required to supply attach locations for these payloads. Additionally, expanded capability will be provided for existing station-provided user services. One area of increased functionality is growth in the data management system (DMS) throughput, storage capacity, and bandwidth. This can be provided as a result of an expandable and upgradeable baseline system design. Another enhancement for station operations could come in the form of an expanded Earth-to-orbit delivery system. To that end, the station will evolve to accommodate cargo delivery via expendable launch vehicles.

New technology provides an avenue by which to maintain a productive research station. Incorporation of new technologies aboard Space Station would serve three main purposes. First, operations costs could be reduced and/or utilization of station could be increased through the use of advanced technologies. As an example, an advanced propulsion system such as Hydrogen - Oxygen propulsion could reduce costs by eliminating a significant number of annual launches to support station reboost. Secondly, crew safety could be enhanced – in this example by removing hydrazine contaminants from the proximity of EVA astronauts. Lastly, but perhaps most importantly for a long duration research facility, is that incorporation of new technologies would postpone obsolescence.

# Utilization Drivers for Growth / Evolution

- **Increase resources for users**
  - Reduce time-sharing of critical resources at PMC
  - Increase utilization by expanding user volume
  - Provide balanced resources

- **Provide expanded functionality for users & station**
  - New classes of payloads (e.g., large external payloads)
  - New functionality within station-provided services such as DMS and C&T
  - ELV delivered cargo

- **Incorporate new technologies**
  - Reduce operations costs and/or increase utilization
  - Increase crew safety
  - Avoid obsolescence

## Utilization Analysis Summary - Mission Requirements Data Sources

Several data sources were surveyed in assessing user requirements. Of primary importance were the NASA supplied "payload traffic models." Each of the user codes (OSSA, OAET, and OCP) publishes their own traffic model which comprises a list of desired payloads to be flown annually for the early years of station operations.

The Level II User Mission Data Base (UMDB) was the primary source for user mission requirements. This data base specifies the crew, volume, and power requirements for the majority of the missions used in this analysis. It also includes mission frequency, i.e., specifications of nominal, peak, and standby periods. Other data sources included the Space Station Freedom Program Utilization Sequence Databook, which provided general laboratory support facilities and laboratory support equipment (GLSF/LSE) volume requirements, and Change Request #BM010173A, "Laboratory Support Equipment Addback," providing GLSF/LSE power requirements. For the International Partner missions, the Memoranda of Understanding (MOUs) provided laboratory volume allocation specifications.

Lastly, the NASA "90 Day Study on Human Exploration of Moon and Mars" was used to determine requirements for vehicle processing operations and R&D supporting the SEI. Specifically, the OSSA provided inputs on life science requirements, the MSFC lunar vehicle specifications, and the NASA KSC vehicle processing analysis were employed in utilization scenarios assessing SEI plus R&D requirements.

## Utilization Analysis Summary

# Mission Requirements Data Sources

- **NASA HQ user representatives-supplied traffic models**
  - Office of Space Science and Applications (11/90)
  - Office of Aeronautics, Exploration, and Technology (6/90)
  - Office of Commercial Programs (6/90)

- **Level II Data**
  - User Mission Data Base, Revision 4.2 (9/90)
  - SSFP Utilization Sequence Databook (10/90)
  - CR# BM010173A, Laboratory Support Equipment Addback

- **International MOU's**

- **NASA 90 Day Study on Human Exploration of Moon and Mars**

## Utilization Analysis Summary

The purpose of this analysis is to identify resource levels needed to support SSF mature operations in the 2005+ timeframe. Since Program options for long term utilization are currently under study, analysis has been performed to evaluated several potential utilization scenarios. These include core research and development (R&D) and combined R&D and space exploration initiative (SEI) scenarios. By studying various user resource allocation schemes for a "core" R&D program and then for an SEI plus R&D program, it was determined that 150 kW of power, thirteen to fourteen crew, and additional laboratory volume equivalent to a U.S. laboratory module will be required to meet both station and user operational needs.

The results are based on an allocation scheme commensurate with a "minimum essential" user capability. To establish this level of utilization, trend analysis was performed to derive resource relationships within specific user disciplines. These interrelationships were then employed in balancing the resources on the growth station to arrive at the stated growth resource requirements of 150 kW, thirteen to fourteen crew, and two U.S. laboratory modules.

# Utilization Analysis Summary

- **Established SSF growth requirements of 150 kW of power, 13 - 14 crew, and the addition of U.S. Lab B**
  - Based on multiple analysis iterations, including Core R&D program and SEI plus R&D support
- **Driver is full utilization of available user resources (i.e., crew, power, volume) commensurate with minimum essential user capability**
  - Resource interrelations established through trend analysis
  - Balanced resources based upon interrelationships

## Utilization Analysis Summary - Payload Trend Data

Derivation of an accommodation methodology which would allow for multiple analysis iterations in a reasonable time span was necessary. Also, since this analysis focuses on user requirements in a timeframe later than user traffic model specifications, there was a need to create "generic" missions which represent average requirements for each user discipline. Consequently, user mission requirements were compiled from several data sources with the goal of reducing hundreds of experiment specifications into a manageable set of experiment characteristics.

Each mission was classified according to one of nine research disciplines: Life Sciences, Microgravity Research, Technology Development (internal and external), Observational Sciences, Commercial Materials Processing, Commercial Life Sciences, External Commercial, and GLSF/LSE.

For each of these mission classes, the mission data were reviewed for "trends" in resource consumption (i.e., power use per double rack, crew use per double rack, etc.). Additionally, interrelationships between resource use among users (e.g., power verses crew for pressurized payloads) were derived to aid in balancing resource capabilities. These newly established trend data were then applied to the allocated user volume to determine total user requirements. Through iterative refinement of the allocation scheme, the resources were balanced in accordance with the interrelationships derived in the trend analysis.

## Utilization Analysis Summary
# Payload Trend Data

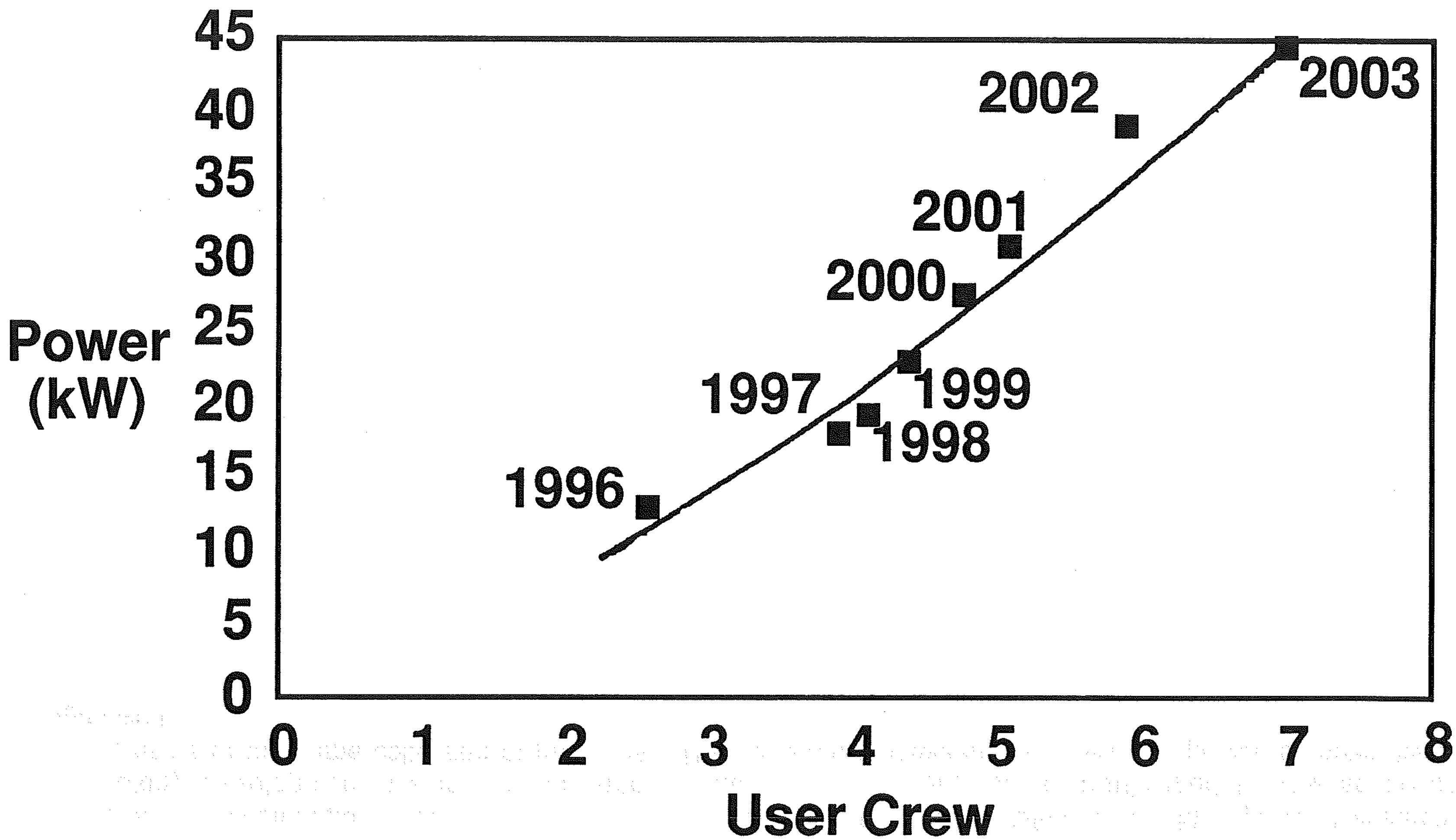
| Discipline | Avg cont. Power (kW) | Crew | Annual Logistics (lb) |
|---|---|---|---|
| **Per ISPR:** | | | |
| Life Sci | 0.91 | 0.09 | 2334 |
| μ-g Research | 2.06 | 0.31 | 1064 |
| TD (internal) | 0.49 | 0.19 | 210 |
| Com'l Mat'ls | 1.08 | 0.13 | 1596 |
| Com'l Life Sci | 0.05 | 0.05 | 812 |
| GLSF/LSE | 0.29 | negligible | negligible |
| **Per APAE-equivalent:** | | | |
| TD (external) | 0.31 | 0.03 | 338 |
| Obs. Sciences | 1.98 | negligible | 1400 |
| Com'l (external) | 0.54 | negligible | 1465 |

430

## Utilization Analysis Summary - Power vs Crew Trends

As an example of resource interrelationships, this chart shows the derived user power versus crew trend for a subset of U.S. payloads. Each datum point plots the combined power requirements for all the Life Science, Microgravity Research, and (internal) Technology Development missions manifested in that year of the appropriate traffic model against the combined crew requirements of the same collection of payloads. The correlation between user crew and power is shown by a second order regression.

## Utilization Analysis Summary
# Power vs Crew Trends*




** Level I Traffic Model missions for internal Life Science, Microgravity Research, and Technology payloads*

# SSF Evolution Requirements - Core R&D Utilization

## SSF Evolution Requirements - Core R&D Utilization - Principal Assumptions

This utilization analysis scenario is based on accommodation of core R&D missions as defined in the NASA payload traffic models and mission data bases. No specific SEI utilization such as vehicle processing or augmented life science mission supporting microgravity countermeasures were included. It should be noted, however, that objectives of some of the core life science and technology development missions do support SEI research requirements.

The timeframe assumed is SSF mature operations in the CY2005+ period. The R&D utilization is strongly oriented toward life science and technology development. It is assumed that many of the early microgravity and materials processing missions have either completed their objectives or have moved off station to dedicated free-flying facilities. Also, the International Partner rack allocation is used to emphasize life science and technology development with resources consistent with similar U.S. missions.

SSF Evolution Requirements - Core R&D Utilization

# Principal Assumptions

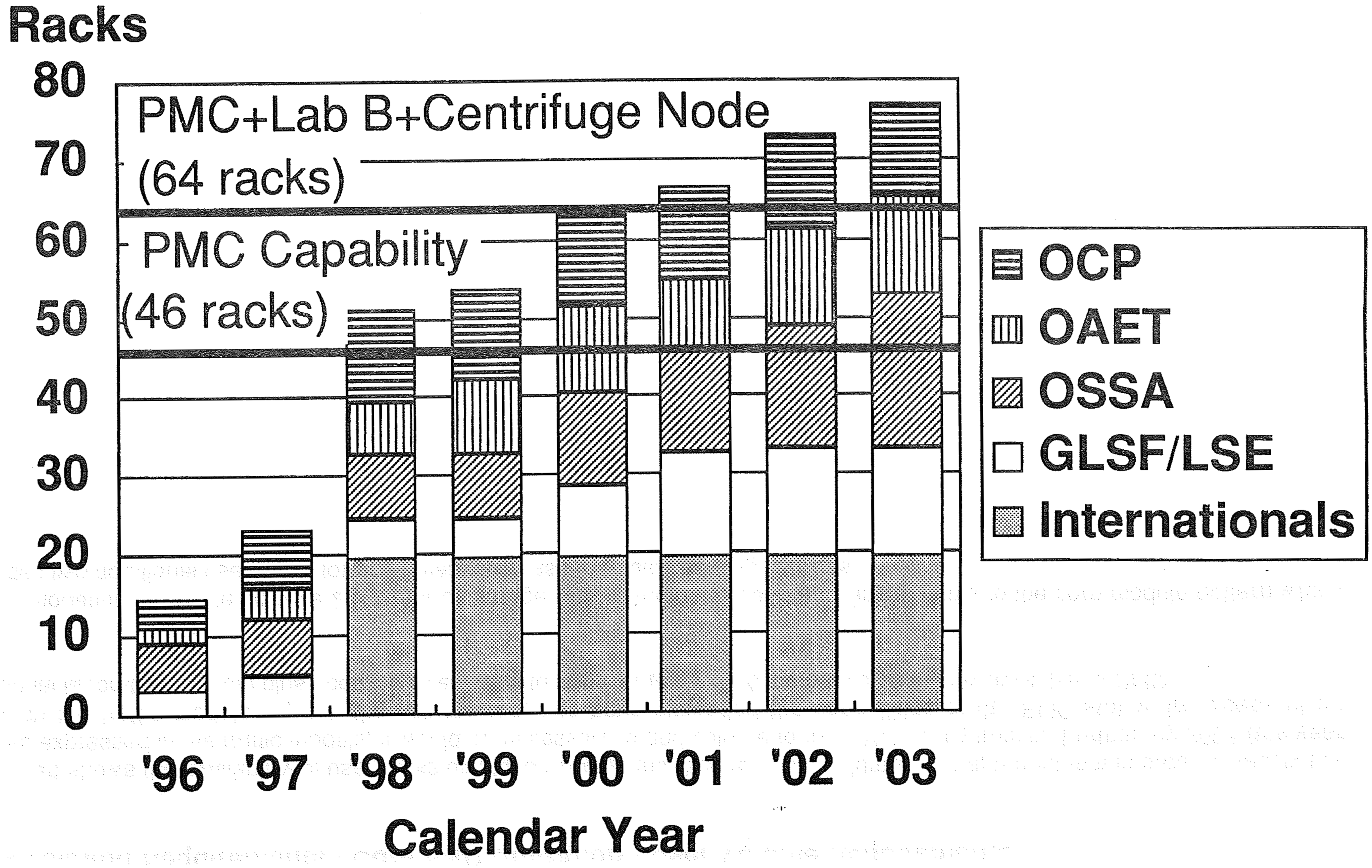
- **Use 1990 Payload Traffic Models as guideline**
- **No dedicated SEI contribution**
- **Allocation scheme**
  - Post 2005 timeframe
  - Strong life sciences and technology development utilization
  - Moderate Microgravity Research accommodation; assumes early microgravity payloads have moved off station
  - Crew and power for international volume consistent with U.S. usage

## SSF Evolution Requirements - Core R&D Utilization - User Volume Requirements

This chart shows the availability of user racks on station versus the required user volume. It is apparent that in order to satisfy the desires expressed in the traffic models, it would be necessary to add volume to the PMC configuration. Further, by 2003 (the year in which the traffic models expire), the volume requests have exceeded the capabilities of the PMC station in excess of an additional laboratory module plus node. This equates to approximately 67% more volume than is available at PMC.

Accommodation of the life science 2.5 meter centrifuge was assumed to be in a facility external to the core module pattern which provides two additional user racks for equipment such as the habitat holding facilities.

## SSF Evolution Requirements - Core R&D Utilization
# User Volume Requirements




438

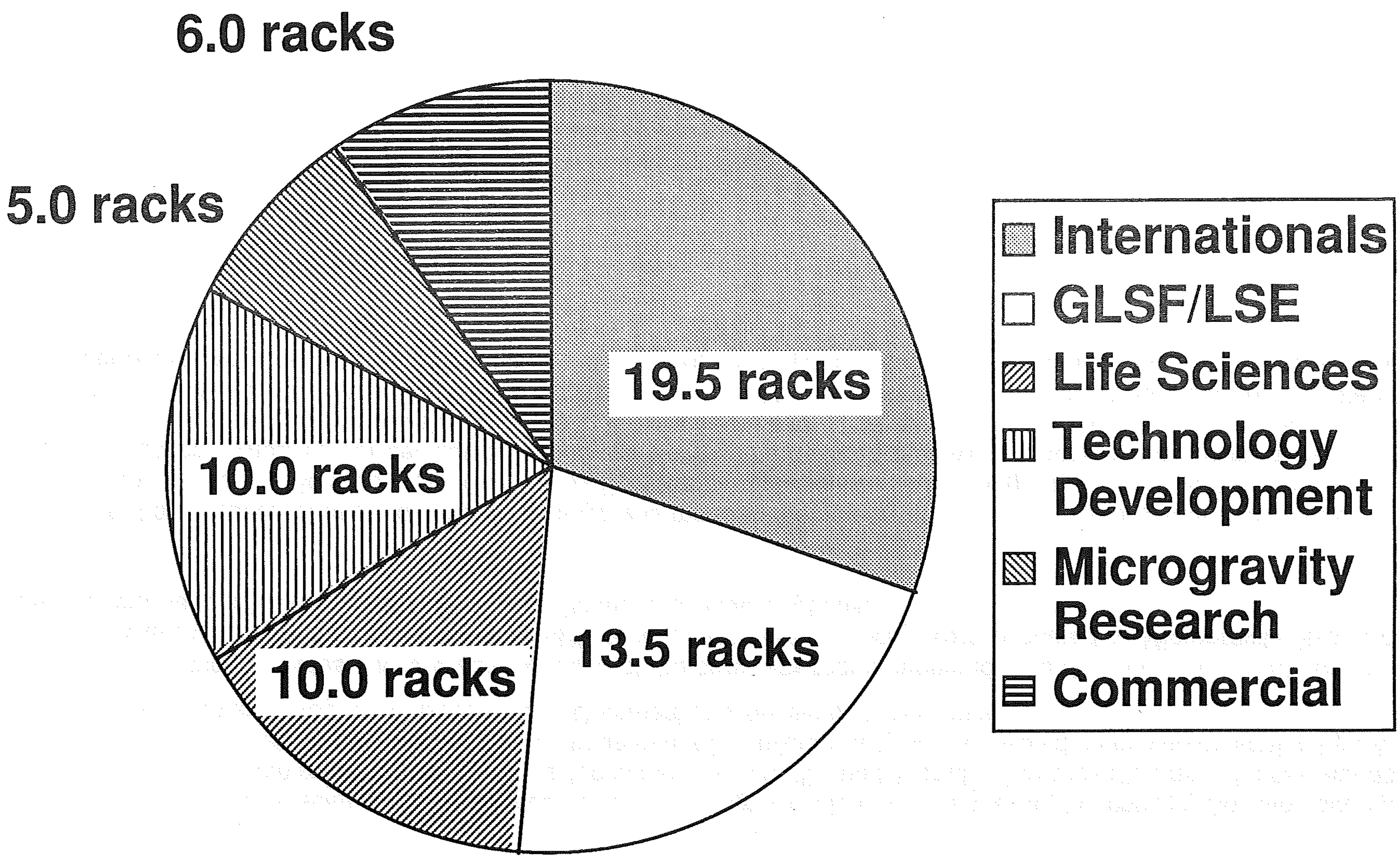
## SSF Evolution Requirements - Core R&D Utilization - User Volume Allocation Scheme

For the Core R&D utilization scenario (Life Sciences and Technology Development emphasis), the chosen allocation attempted to accommodate the maximum number of racks requested in the OSSA traffic model for Life Sciences (10), and of racks requested in the OAET traffic model (12). It was assumed that fifty percent of all microgravity science would be moved off station by this time, so the racks allocated to Microgravity Research and Commercial users were roughly one-half of their traffic model requests.

The resultant allocation provides 100% accommodation of the core rack requirements for Life Sciences (10 racks), and an equal number of racks for Technology Development (83% of request). Eleven racks were allocated to Microgravity Research and Commercial payloads (50% of request) in keeping with the above assumptions.

In addition to the allocation of user volume, an attempt was made to identify an attached payload program appropriate to a core R&D utilization. Since Life Sciences and Technology Development disciplines were being emphasized, and since Life Sciences sponsor no attached payloads, four dedicated Technology Development attach sites were allocated to accommodate an attached program at least as robust at that developed in the OAET traffic model. (This assumed some attach sites can support multiple small payloads). It was further assumed that the large proposed OSSA attached payloads that could not be accommodated earlier in station operations would also be accommodated. To this end, three attach sites were allocated for Astromag-class payloads.

## SSF Evolution Requirements - Core R&D Utilization
# User Volume Allocation Scheme*



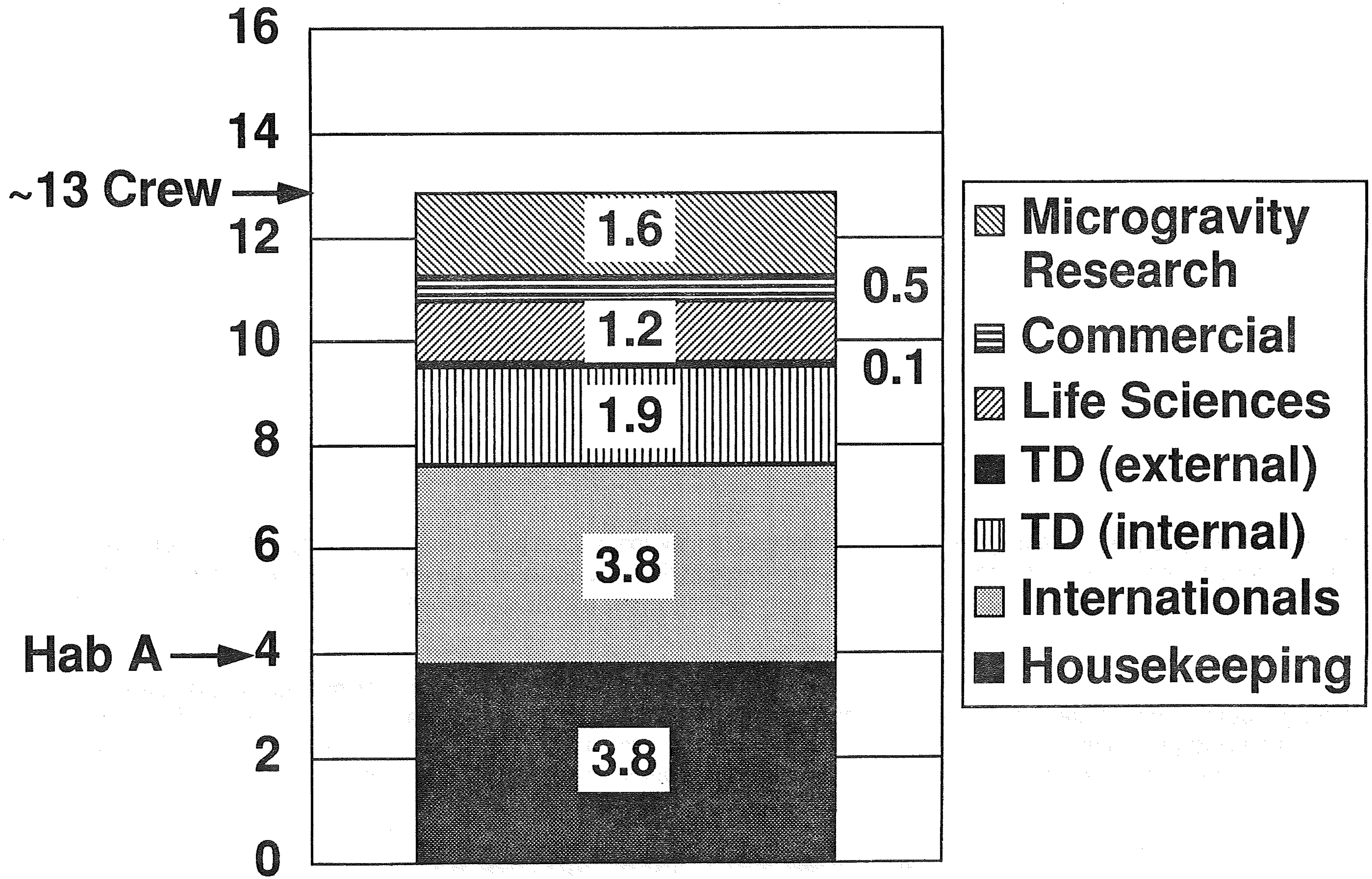

*64 user racks

## SSF Evolution Requirements - Core R&D Utilization - Crew Requirements

Thirteen crew are required to meet this allocation of payloads, with over 20% of the user crew attributable to Technology Development payloads. Crew requirements for specific user disciplines are shown as segments within the bar graph. The crew housekeeping specification of 3.8 crew is the result of a first order estimate based on total pressurized volume. Studies are currently underway to refine this estimate.

Growth habitation modules will be required to house the additional nine crew required by this core R&D utilization scenario. Assuming each habitation module houses four crew, this implies four total habitation modules. The actual number of habitation modules required is dependant upon system and crew accommodation facility requirements in the growth habitation modules.

# SSF Evolution Requirements - Core R&D Utilization
# Crew Requirements

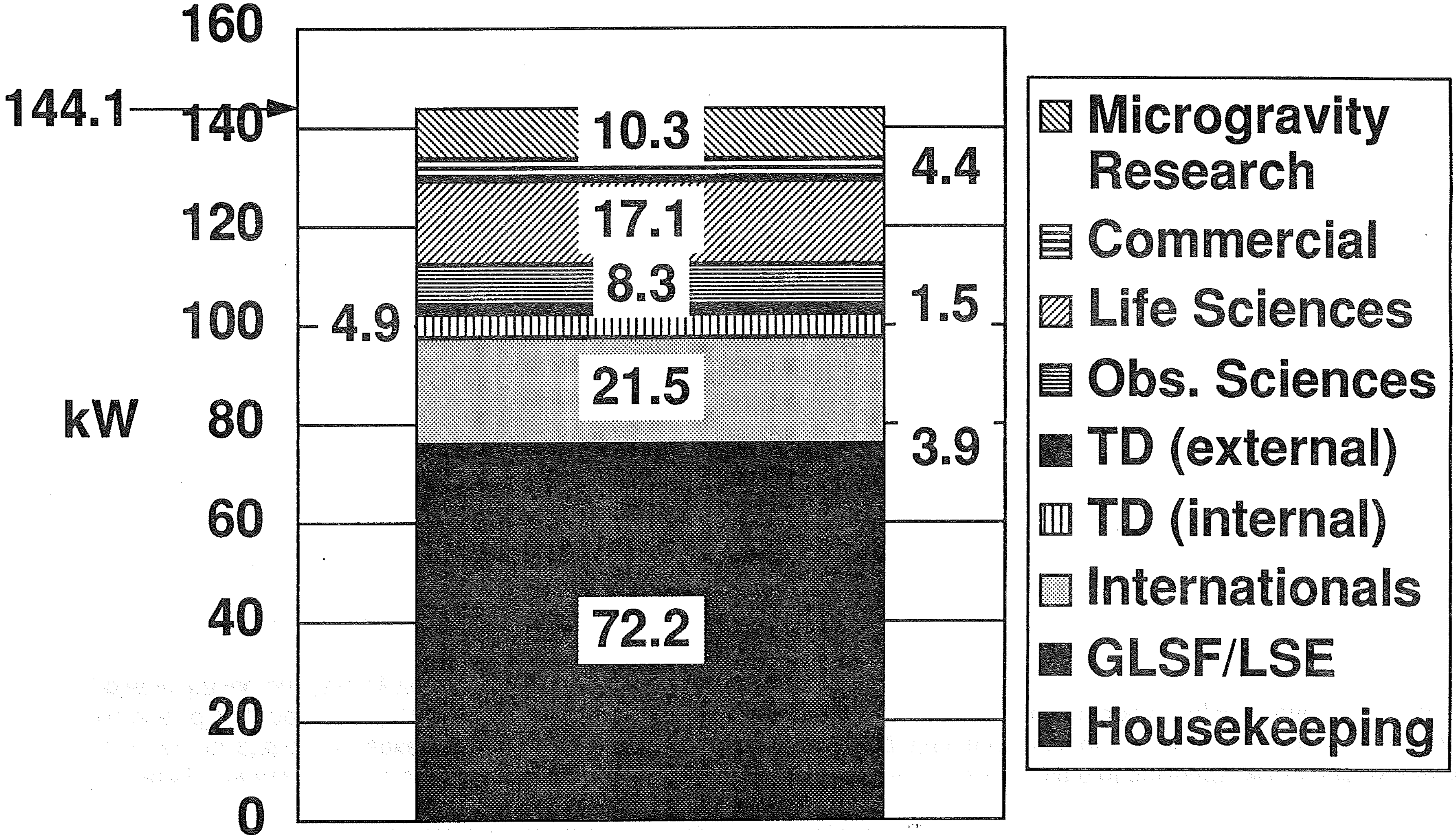


## SSF Evolution Requirements - Core R&D Utilization - Power Requirements

Approximately 144 kW average power generation capability is required to meet this allocation of payloads, with ~50% of the power load required for station housekeeping, i.e., non-user equipment including station distributed systems. Power requirements for specific user disciplines are shown as segments within the bar graph. The power housekeeping requirement of 72.2 kW is an extrapolation based on PMC system requirements.

SSF Evolution Requirements - Core R&D Utilization

# Power Requirements



## SSF Evolution Requirements - Core R&D Utilization - Growth Structure Requirements

This utilization analysis has driven out growth structure requirements for several purposes. Growth structure is required to extend the solar power booms so that additional power generation equipment may be added outboard of the solar alpha joints. Also, growth structure which is orthogonal to the pre-integrated truss transverse boom is required to provide additional external attach locations. This external volume is necessary for user attached payloads and is also required to support equipment associated with growth systems, e.g., equipment needed for an advanced propulsion system. Also, the additional external attach volume will provide valuable storage locations for spare hardware and EVA equipment.

An important additional aspect of the orthogonal growth structure is the flexibility it would provide in the growth plan for Freedom. For example, the growth structure could allow for cargo transfer vehicle storage (required by ELV cargo delivery system), for servicing of contamination sensitive free flyers, and/or for SEI vehicle processing and hangaring. (In fact, the SEI vehicle processing and hangaring were assumed to be accomplished in this very manner in the SEI plus R&D utilization scenario).

## SSF Evolution Requirements - Core R&D Utilization

# Growth Structure Requirements

- **Ability to add structure to the baseline PIT is required for**
  - Extension of the power booms to support growth power
  - Accommodation of orthogonal structure

- **Orthogonal growth structure provides necessary attach locations and volume for**
  - External attached payloads
  - Growth distributed system components such as $H_2$ - $O_2$ propulsion ORUs, growth TCS ORUs, etc.
  - Storage of external equipment and spares

- **Also provides flexibility in the growth path, i.e., may accommodate facilities for**
  - CTV storage
  - Servicing of contamination sensitive free flyers
  - SEI vehicle processing/hangaring

# Summary & Conclusions

- **SSF user growth requirements have been assessed through multiple analyses, using sanctioned user inputs**
  - User resource trends established
  - "Core R&D" and "SEI plus R&D" scenarios
  - Varying allocation assumptions

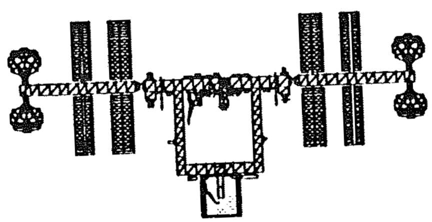


- **Analysis approach is based on balancing resources (i.e., crew, power, volume) commensurate with minimum essential user capability**

- **Key SSF evolution requirements have been derived**
  - Pressurized volume (user and crew habitat )
  - Power/Thermal
  - Structure

Space Station Evolution
Beyond the Baseline

# SSF Growth Concepts & Configurations



William M. Cirillo
NASA Langley Research Center
SSFO/APO
August 7, 1991

Space Station Evolution
Beyond the Baseline

# SSF Growth Concepts & Configurations

William M. Cirillo
NASA Langley Research Center
SSF-[illegible]
August [illegible]

## OBJECTIVES

There are three primary objectives for the Space Station Freedom (SSF) Growth Concepts and Configurations study task.

The first objective is the development of evolutionary SSF concepts consistent with user requirements and program constraints. In the past this objective has been met by defining separate evolution growth concepts for the support of different classes of user missions, such as multidisciplinary research and development concepts and Space Exploration Initiative (SEI) transportation node concepts. The approach that is now being used is to derive the full set of user mission requirements for both R&D and SEI and integrate them into one set of SSF evolution concepts, referred to as continued development phases.

A detailed discussion of SSF user requirements and an overview of the methods used to derive the requirements for the restructured SSF is provided in a paper by Kevin Leath, Rudy Saucillo, and Karen Brender entitled, "Evolution User Requirements for the Restructured Space Station" enclosed in this volume. The final results of their analysis conclude that independent of which user mission model (SEI or R&D) is used, the total end user requirements are nearly identical. The results indicate that approximately 150 kW of power, a crew of 13-14, and additional laboratory volume equivalent to the first U.S. Laboratory module are required to meet future user needs. In addition, orthogonal growth structure is required to support SSF systems and user needs.

The second primary objective is to ensure the feasibility of the proposed SSF evolution concepts at the system level. This includes, but is not limited to, an assessment of SSF evolution flight control analysis, logistics assessment, maintainability, and operational considerations.

The final objective is to ensure compatibility of the baseline SSF design with the derived evolution requirements at both the system and element (habitat modules, power generation equipment, etc.) levels.

# SSF Evolution Configuration Assessment

## Objectives

- Develop evolutionary concepts for Space Station Freedom consistent with user requirements and program constraints
- Ensure feasibility of evolution concepts at the system level (controllability, logistics, maintainability, etc.)
- Ensure compatibility of baseline design with evolution requirements at the system (e.g., configuration) and element (e.g. habitation module) levels

## PRODUCTS

The main product of this study is the development of SSF evolution configuration phases and growth hardware elements. Each evolution phase description will provide an overview of functional capabilities, physical characteristics, and performance characteristics. The physical characteristics include the identification of each phases mass, inertias, ballistic coefficient, and center of gravity. Each of these items is used to drive the Langley Research Center's in-house performance analysis tool, IDEAS 2. IDEAS 2 has the capability to perform simulation of vehicle flight dynamics, orbital lifetime, and reboost propellant assessment. In addition, graphic representations of the various evolution concepts are provided to further enhance study and design activities.

The primary source for collection of configuration analysis is the SSF Engineering Data Book, which was developed and is maintained at Langley Research Center.

Another important product of this study is the development of element growth concepts. This includes performing cost and weight trades, assessing the impacts on the baseline design of either incorporating or not incorporating the different growth elements, and performing a preliminary operational assessment. This process will allow the identification of critical scars that need to be included in the baseline SSF design, as well as, provide for an initial input to the subsystem designers for detailed design-for-growth activities.

## SSF Evolution Configuration Assessment

# Products

- Configuration descriptions of evolution phases and growth elements
  - Primary input to the Engineering Data Book and associated data books
  - Groundrule data for distributed systems and operations tasks
- Element growth concepts including cost and weight trades, impacts on baseline design, operational impacts, and impacts of non-inclusion of design accommodations
  - Allows identification of "critical scars" and provides subsystem designers a "running start" on detailed design-for-growth activities

## APPROACH AND METHODOLOGY

The approach used to develop the SSF evolution configurations has three primary steps. The first step involves the completion of the individual SSF advanced studies to the point where configuration inputs to the study are critical. As an example, the module pattern trade study which is currently being conducted has several trades, such as node to module interface concerns and remote manipulator reach access, which can be assessed independent of overall SSF configuration design. On the other hand, such trades as module pattern impact on SSF flight attitude and viewing obstruction assessments, can only be performed using an integrated SSF configuration which takes into account the results of other trade studies that are being conducted concurrently.

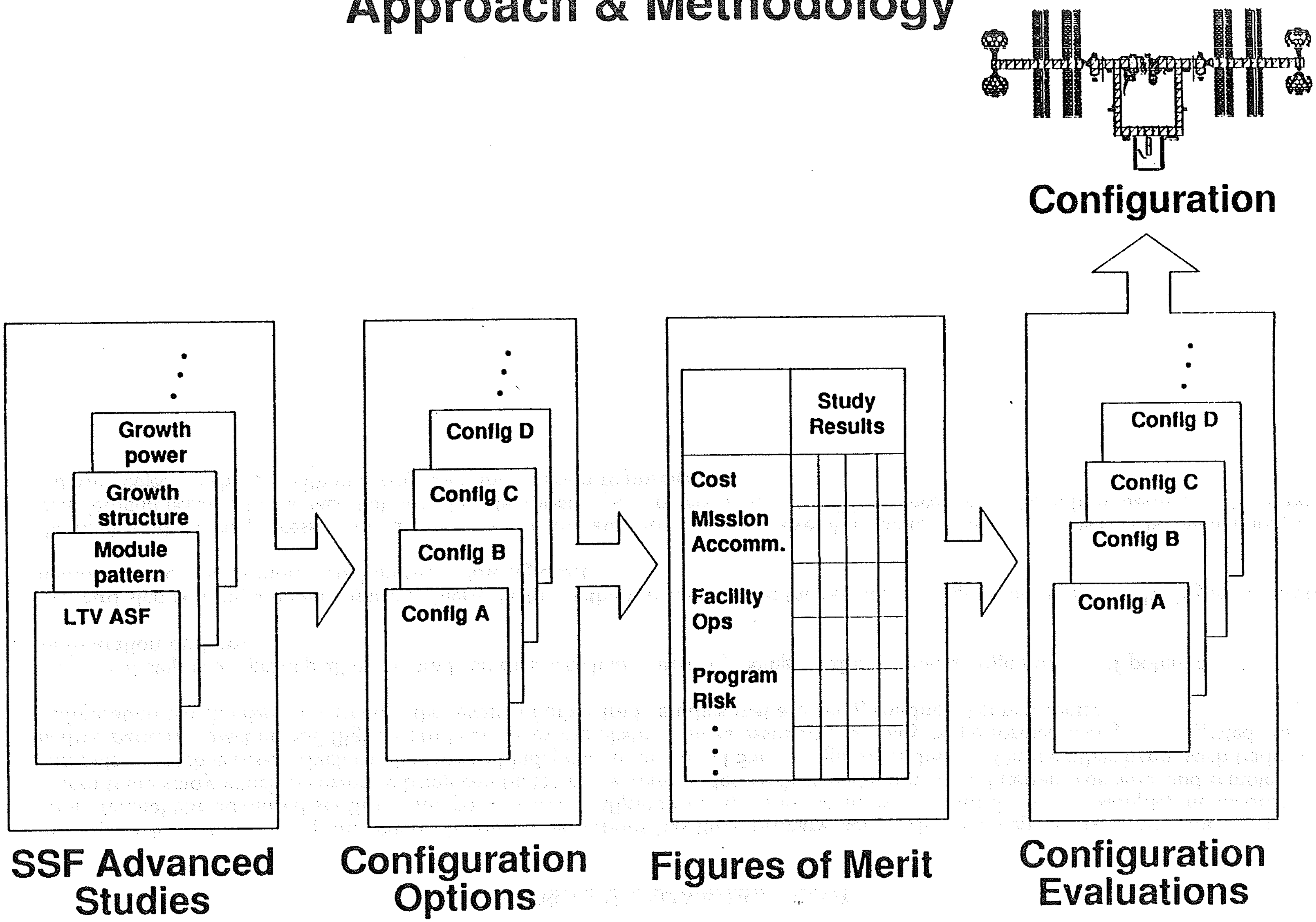
The second step is integrating all of the trade studies which are currently being conducted into a large number of potential configuration options.

The third step is using a tiered, Figure of Merit (FOM) method to assess all of the possible configuration options. The Figure of Merit method is described in more detail on the following chart.

The final result of the process is the ranked series of configuration options. Several of the top ranked options will be maintained for consideration because of the fact that not all of the mission parameters used in the FOM process have been fully defined at this time and are subject to change with evolving user and mission requirements.

## SSF Evolution Configuration Assessment

# Approach & Methodology



## TIERED FIGURES OF MERIT

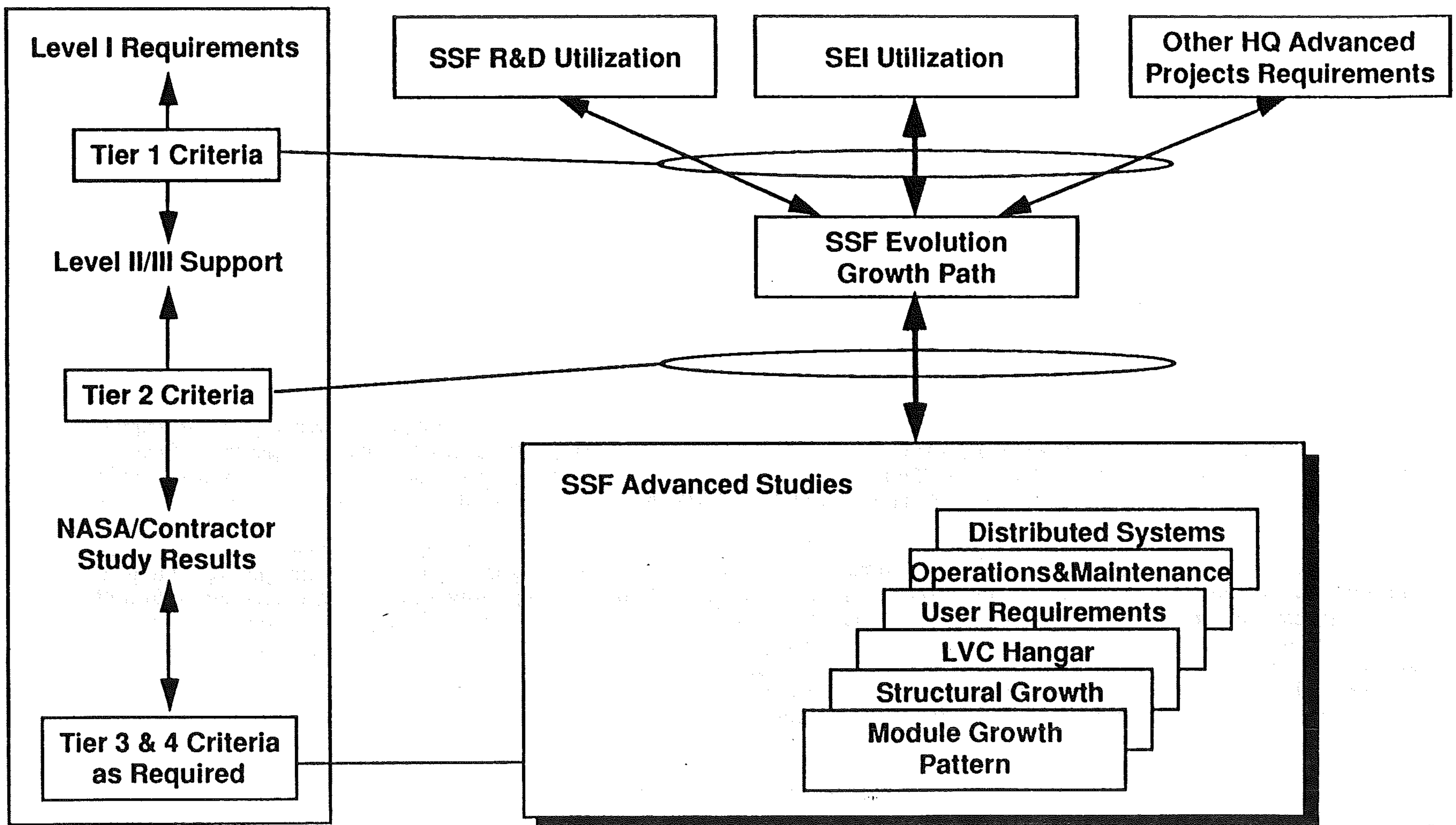
In order to handle the large trade space that results from the SSF evolution configuration process described earlier a method based on utility theory, which transforms both quantitative and qualitative criteria into non-dimensional utility scale for comparison of dissimilar figures of merit, is chosen. This benefits of this method are that the process is systematic, retraceable in nature, and allows for interaction among the key decisions makers that are involved. The utilization method used in this study consists of he following major steps, (1) identification of the Figures of Merit (criteria); (2) ranking of the criteria in order of importance; (3) weighting of the criteria based on rankings; (4) measuring each SSF evolution concept with respect to the selection criteria and then normalizing; (5) multiplying a set of derived utility values by the criteria weight and summing; (6) ranking the SSF evolution concepts based on the weighted utilities.

A further detailed description of this entire process is provided in a paper by J.E. Hendershot, McDonnell Douglas Space Systems Company, R.R. Corban and S.M. Stevenson, NASA Lewis Research Center, entitled, "Fuel Systems Architecture Evaluation Criteria and Concept Evaluation Methodology", AIAA 91-3479, as part of the AIAA/NASA/OAI Conference on Advanced SEI Technologies, September 4-6, 1991, Cleveland, Ohio.

## SSF Evolution Configuration Assessment

# Tiered Figures of Merit

Tiered Figures of Merit



EVALUATION CRITERIA

The Tier 1 and Tier 2 Figures of Merit (Evaluation Criteria) are shown. A detailed discussion of each of the criteria is currently being developed under separate cover.

# SSF Evolution Configuration Assessment

## Evaluation Criteria

**TIER 1** / **TIER 2**

- **COST**
  - BASELINE SCAR COST
  - GROWTH COST (POST PMC)
- **MISSION ACCOMMODATION**
  - SEI ACCOMMODATION
  - R & D ACCOMMODATION
  - INTERNATIONAL ACCOMMODATION
  - MISSION FLEXIBILITY
- **FACILITY OPERATIONS**
  - ASSEMBLY
  - LOGISTICS
  - EXTERNAL SYSTEM INTERACTION
  - HOUSEKEEPING
  - MAINTENANCE
- **PROGRAM RISK**
  - COST RISK
  - SCHEDULE RISK
- **PERFORMANCE RISK**
  - CONCEPT COMPLEXITY
  - TECHNOLOGICAL RISK
  - DESIGN FLEXIBILITY
  - OPERATIONAL RISK
- **SAFETY**
  - IVA
  - EVA
  - MANNED VEHICLE OPERATIONS

## CONFIGURATION DEVELOPMENT

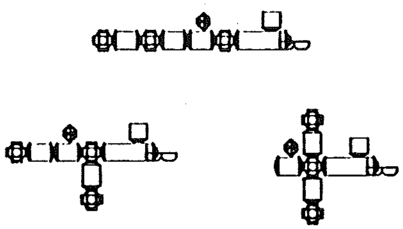
The development of potential SSF evolution configuration candidates involves the inputs of a multitude of on-going SSF trade studies as shown in the accompanying illustration. Four of the trades will be discussed in more detail in the following charts. They are the module pattern study, the life sciences centrifuge facility location study, the growth structure study, and the Lunar Transfer Vehicle (LTV) Assembly Servicing Facility (ASF) study.

At present, most of these studies are on-going, so a final ranking of all of the possible SSF evolution configurations has not been completed. A set of rapid prototype evolution configurations has been developed based on the trades that have been completed to date and are shown at the end of the presentation. These rapid prototype configurations were developed in order to provide a preliminary set of SSF evolution phase concepts to those advanced systems studies that need configurations against which to perform their respective trade studies.

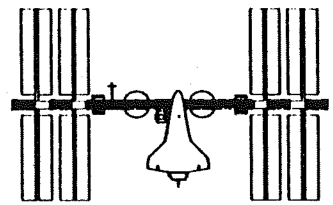
NASA FREEDOM

## SSF Evolution Configuration Assessment

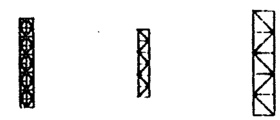
# Configuration Development



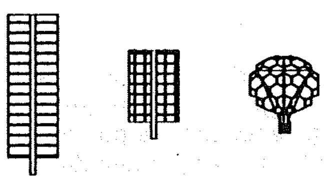
**Module Pattern/ Centrifuge**



**Candidate Evolution Configurations**



**Growth Structure/ Utility Distribution**



**Power Generation**

- Operations
- Distributed Systems
- Logistics
- NLS/CTV Interfaces
- Distributed Systems

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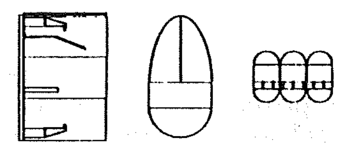


**LTV Vehicle Accommodation**

LaRC SSFO

KCS 5/13/91 10:30

## MODULE PATTERN STUDY OBJECTIVES

Based on the number of changes to the baseline SSF configuration that have resulted from the resent SSF Restructuring activity (segmented modules vs. 44 ft., lower total pressurized volume, etc.) it was determined to re-evaluate the SSF evolution module pattern assessment that was performed two years earlier in order to determine the most favorable SSF evolution module pattern. As previously discussed, this trade focuses primarily on module pattern specific issues such as external operations and utility interfaces between module pattern elements. Areas such as flight attitude and viewing will need to take into account other trade study results which involve the use of an integrated SSF evolution configuration concepts.

## Module Pattern Growth Concepts

# Study Objectives and Restructuring Issues

- **In light of recent SSFP changes, options for module pattern growth are being revisited. Differences from previous trade study include:**
    - Growth from PMC vs. AC
    - Segmented modules vs. 44 ft modules
    - Module addition along transverse boom not possible due to TCS radiator location
    - Lower total pressurized volume requirements
- **Analysis is inititally focusing on *module pattern-specific* issues**
    - External operations including growth pressurized element assembly and Shuttle payload exchange
    - Utility interface and baseline scar requirements
- **After other utilization/configuration issues are resolved; additional analyses will be performed**
    - TEA, momentum management, microgravity environment
    - Viewing
    - Etc.

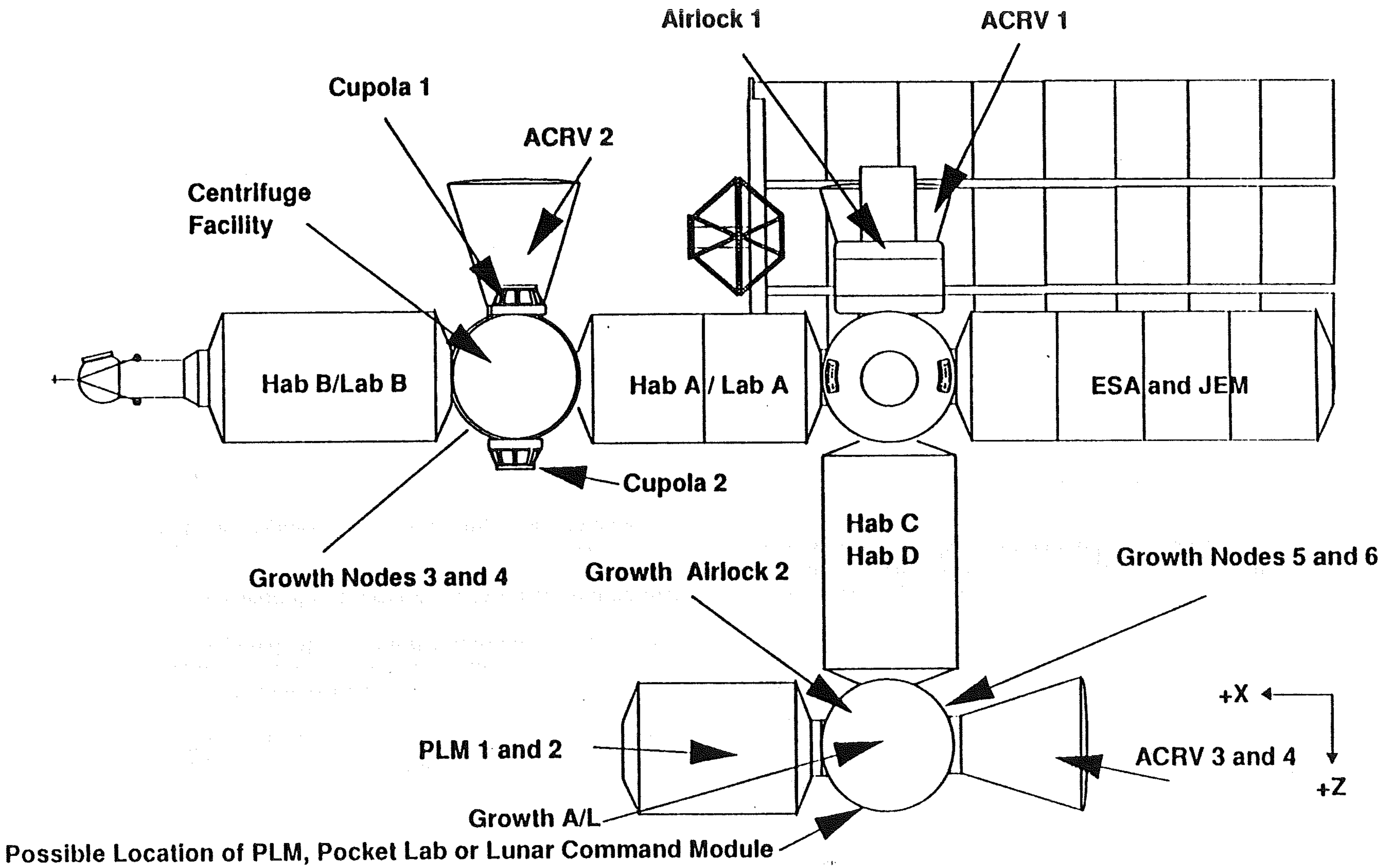
## EVOLUTION MODULE PATTERN

The SSF evolution module pattern shown has been designed to accommodate the SSF utilization resource requirements determined earlier. The evolution module pattern begins with adding one additional habitat and one additional laboratory module, along with two resource nodes, to the PMC module pattern, in the direction of flight. Additionally, a second four man Assured Crew Return Vehicle (ACRV) is added on the zenith side of the starboard growth node.

The next phase of module pattern growth adds two habitat module and two resource nodes in the nadir direction from the baseline resource nodes as illustrated. The two additional nodes allow for attachment locations for the two pressurized logistics carriers which are now required, along with the third and fourth ACRVs.

The benefits of this module pattern over previously studied module patterns is that it provides better viewing of SSF operations from the cupolas, provides additional resource node attach points for future pressurized elements, and requires shorter utility runs for growth elements. This configuration still does solve all of the problems associated with evolution module pattern assembly and operations, but does represent the best configuration to date.

# LVC



Airlock 1
ACRV 1
Cupola 1
ACRV 2
Centrifuge Facility
Hab B/Lab B
Hab A / Lab A
ESA and JEM
Cupola 2
Hab C
Hab D
Growth Nodes 3 and 4
Growth Airlock 2
Growth Nodes 5 and 6
+X
+Z
PLM 1 and 2
ACRV 3 and 4
Growth A/L
Possible Location of PLM, Pocket Lab or Lunar Command Module

## CENTRIFUGE STUDY SCOPE

The purpose of the life sciences centrifuge study is to access the post-PMC accommodation options for a pressurized 2.5 meter centrifuge facility and recommend an implementation with minimum impacts to the baseline program. The study includes an assessment of node accommodation of the centrifuge verse alternative options, attachment location options, and a utility requirements and resource impacts assessment. In addition, the study will identify centrifuge facility drivers and options for the evolution phase module pattern.

# Centrifuge Study Scope

- Purpose of study is to assess post-PMC accommodation options and recommend an implementation with minimum impact to the baseline design
  - Node accommodation vs. alternatives
  - Attach location options
  - Utility requirements and resource impacts

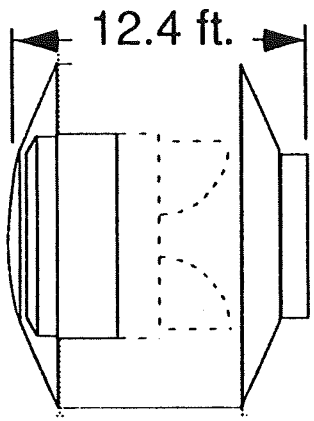
- An additional objective is to identify centrifuge facility location drivers/options for the Evolution Phase module pattern

## LIFE SCIENCE CENTRIFUGE ACCOMMODATION OPTIONS

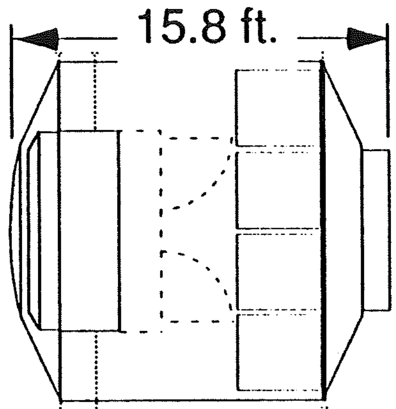
In addition to using a common resource node as is currently being proposed, this study investigates using four alternate pressurized facilities as shown. Each of the facilities provides differing amounts of rack space to the user, which is a primary importance to the life science community. A minimum of two double racks is currently required in order to meet the basic life science user requirements. In addition, a number of SSF system racks, based on pressurized volume amount, must be accommodated in each element.

This study is currently undergoing final review. A more complete report detailing the pros and cons of the various options will be available from the LaRC SSFO in the near future.

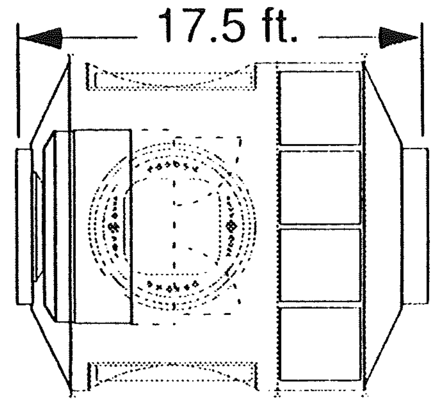
# Life Science Centrifuge Accommodation Options



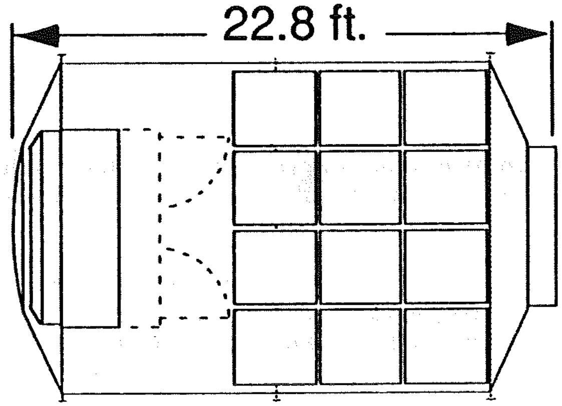

**Mini-PLM**



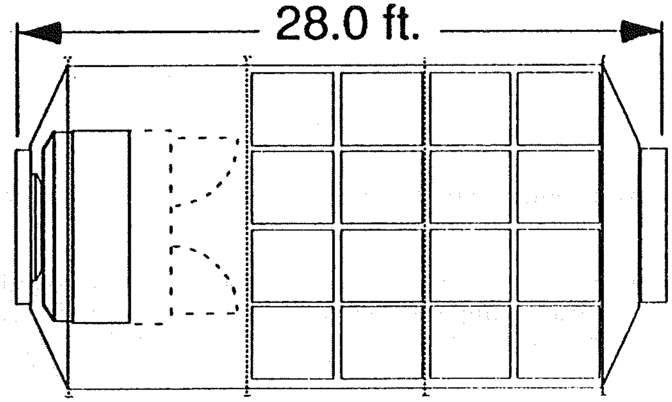

**Italian Mini-lab**




**Resource Node**




**20 Rack PLM**




**Laboratory Module**

## LOCATION ISSUES AND OPTIONS OVERVIEW

Several of the issues associated with the various location options are shown.

# Location Issues & Options

## Overview

**Node 1 Outboard +Y Port (available)**

Issues

Limited Volume due to Radiator Clearance Envelope

Reduced Radiator Performance

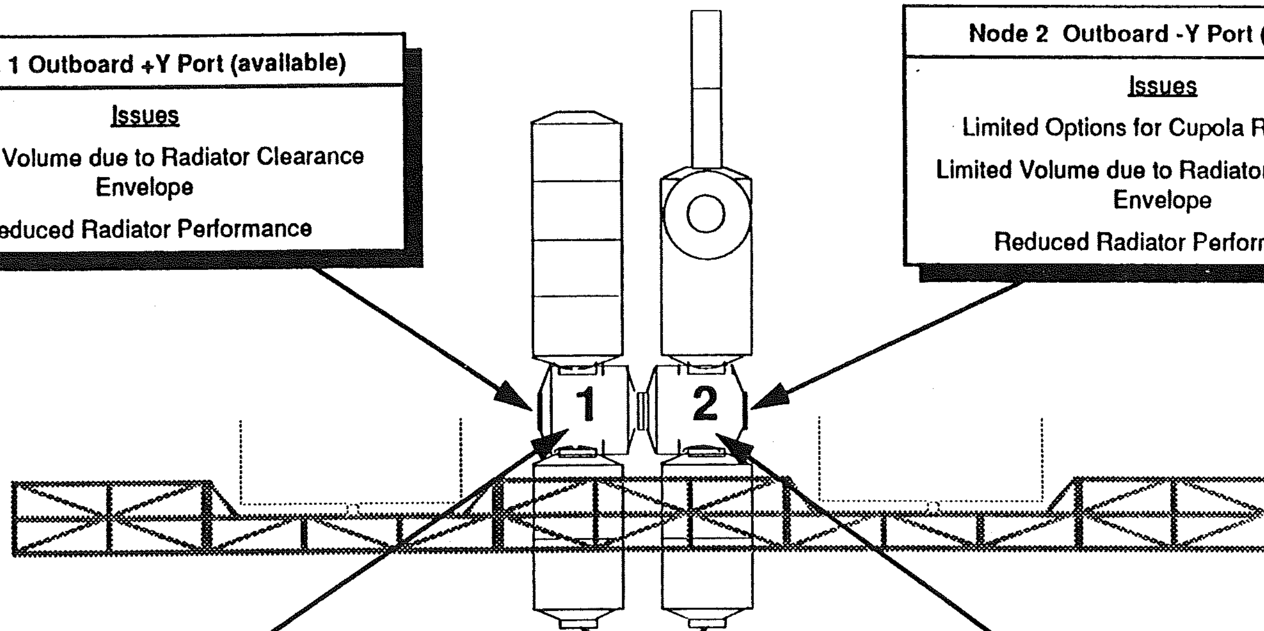
**Node 2 Outboard -Y Port (Cupola)**

Issues

Limited Options for Cupola Relocation

Limited Volume due to Radiator Clearance Envelope

Reduced Radiator Performance




**Node 1 -Z Port (Airlock)**

Issues

No Alternative for Displaced Element

**Node 1 +Z Port (PLM)**

Issues

Impact to PLM Exchange Operations

Violation of PLM Exchange Requirement

**Lab/Hab +X Port (Press Docking Adapters)**

Issues

Crew Egress/Passage Requirement Violation

Limited Bio-Isolation

Eliminates Backup Shuttle Docking Location

**Node 2 -Z Port (ACRV)**

Issues

No Alternative for Displaced Element

**Node 2 +Z Port (PLM)**

Issues

Impact to PLM Exchange Operations

Violation of PLM Exchange Requirement

STRUCTURAL GROWTH STUDY OVERVIEW

The primary purposes of the structural growth study are (1) to develop a number of transition structure concepts which will permit the addition of various growth structure orthogonal to the pre-integrated truss (PIT) transverse boom structure; (2) develop physical concepts for the attachment of a transition structure to the PIT and identify any necessary scars; (3) determine what structural scars, if any, are necessary to allow the addition of growth power modules outboard of the solar array rotary joint (SARJ). In addition to these primary objectives this study will develop concepts for routing and installation of additional utility lines associated with additional power modules and growth in baseline SSF systems.

Also, this task will develop finite element models of several growth configuration concepts to be used in performing dynamic loads analysis to assess the structural response and integrity of the growth concepts for various SSF operations. These operations will include SSF reboost, Shuttle docking/berthing, and plume impingement effects.

# Structural Growth Study

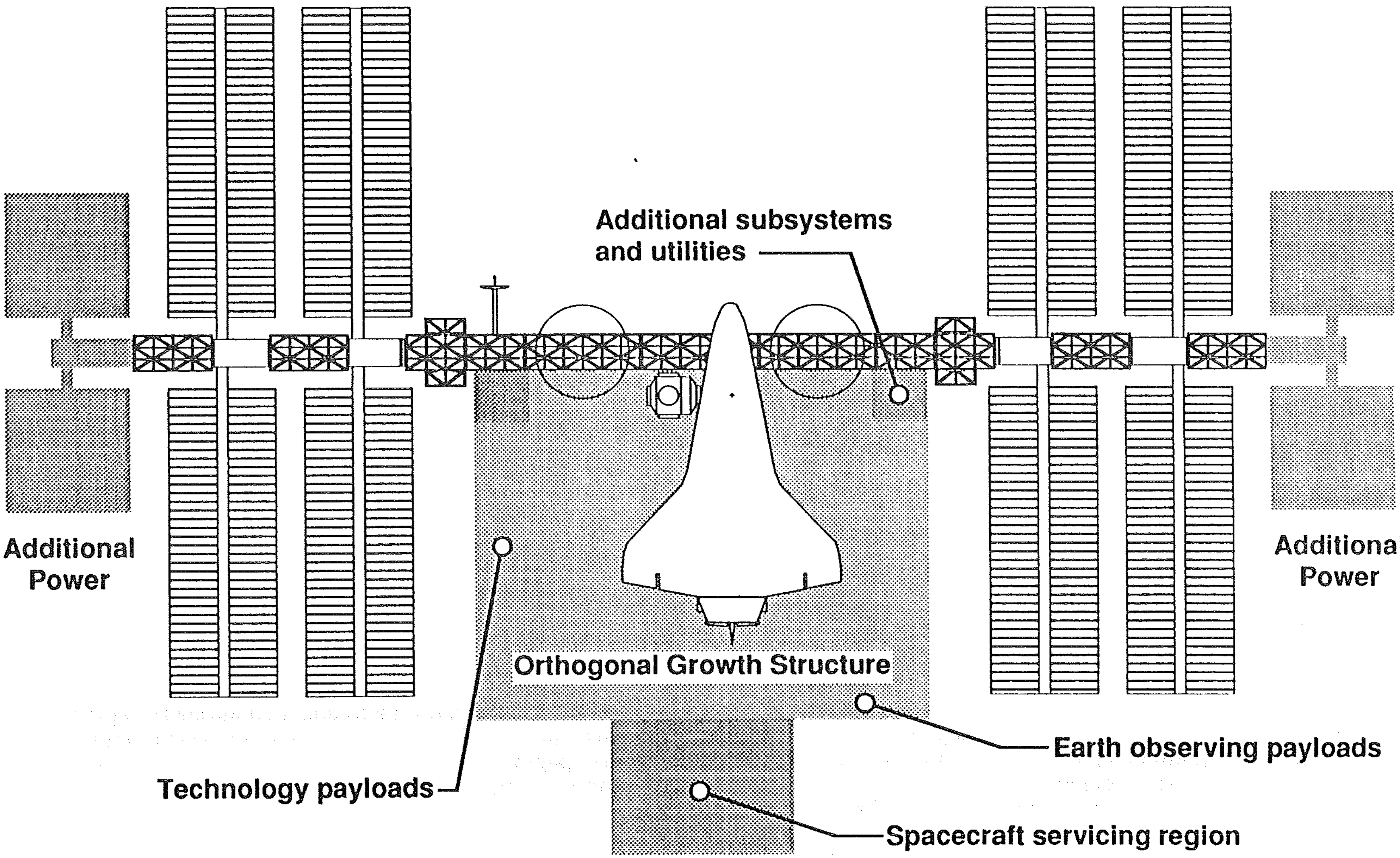
**Define and analyze structural growth options for restructured Space Station Freedom Pre-Integrated Truss (PIT).**

- Develop transition structure concepts which will permit the addition of growth structure orthogonal to the PIT.
- Develop concepts for the physical attachment of a transition structure to the PIT and identify necessary scars.
- Determine what structural scars are necessary to allow the addition of growth power modules outboard of the SARJ.
- Develop concepts for routing and installation of additional utility lines associated with the addition of growth power modules and orthogonal growth structure.
- Develop finite element models of growth configuration concepts.
- Perform dynamic loads analysis of configuration models.

## GROWTH STRUCTURE

Illustrated are the primary drivers and their potential locations which will impact the attachment of growth structure to the baseline SSF configuration. As mentioned earlier, additional power generation capability must be accommodated outboard of the SARJ. Additionally, growth structure will need to be added orthogonally to the transverse boom to accommodate growth of SSF systems, such as thermal control radiators and cryogenic pallet storage, accommodation of earth observing and technology payloads, and eventually the accommodation of an orbital spacecraft processing facility.

# Orthogonal Growth Structure

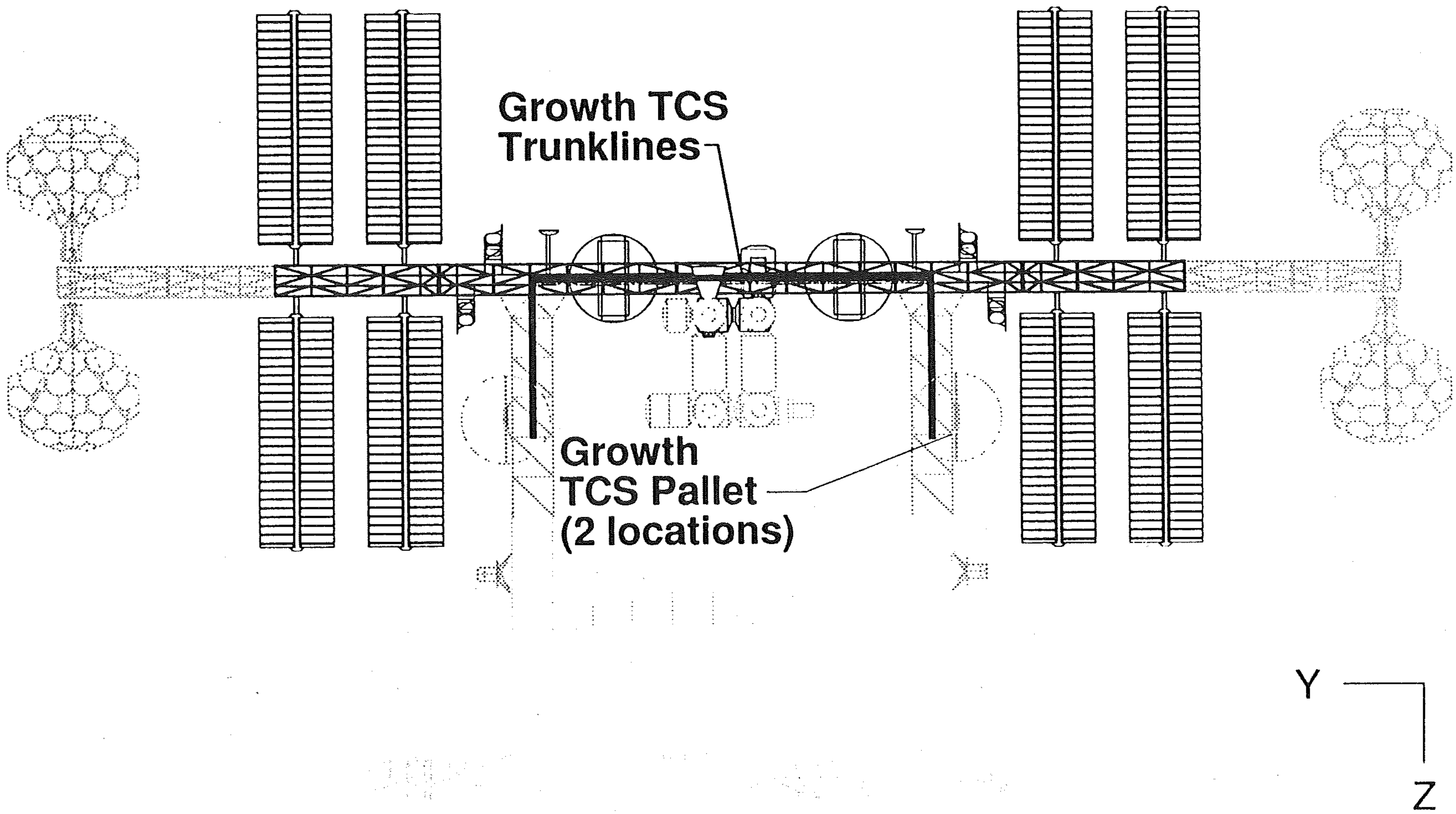


## THERMAL CONTROL SYSTEM GROWTH LOCATION

The location of growth radiators and their associated distribution lines is shown to illustrate the potential for their accommodation on a set of lower keels and boom.

## PIT Growth Utility Requirements

# Thermal Control System



## LUNAR TRANSFER VEHICLE ASSEMBLY SERVICING FACILITY TASK

The final study task to be discussed is the development of an assembly servicing facility (ASF) to process lunar transfer vehicles (LTV). This task is responsible for the engineering and configuration definition of a facility that process LTVs, including determining orbital debris/micrometeoroid protection schemes, thermal control systems, and propellant management systems. In addition, the task will assess and define operations and processing systems that are required to service the LTV including, IVA, EVA, and robotics systems.

This task is currently scheduled for completion in late September 1991, with a final report due out in October.

SSF Evolution Configuration Assessment

# LTV Assembly Servicing Facility Task

- Determine LTV Assembly Servicing Facility Requirements
- Engineering and Configuration Definition of LTV ASF
  - Orbital debris/Micrometeoroid Protection
  - Thermal Control System
  - Propellant Management (Handling, Storage, Transfer)
  - Other systems as required [Lighting; Logistics (spares stowage; robotics; checkout)]
- Operations and Processing Systems Definition
  - Level of A&R required
  - EVA and IVA systems
  - Orbital Support Equipment (OSE) design and capabilities
- On-orbit aerobrake assembly requirements
- Interfaces with existing SSF systems

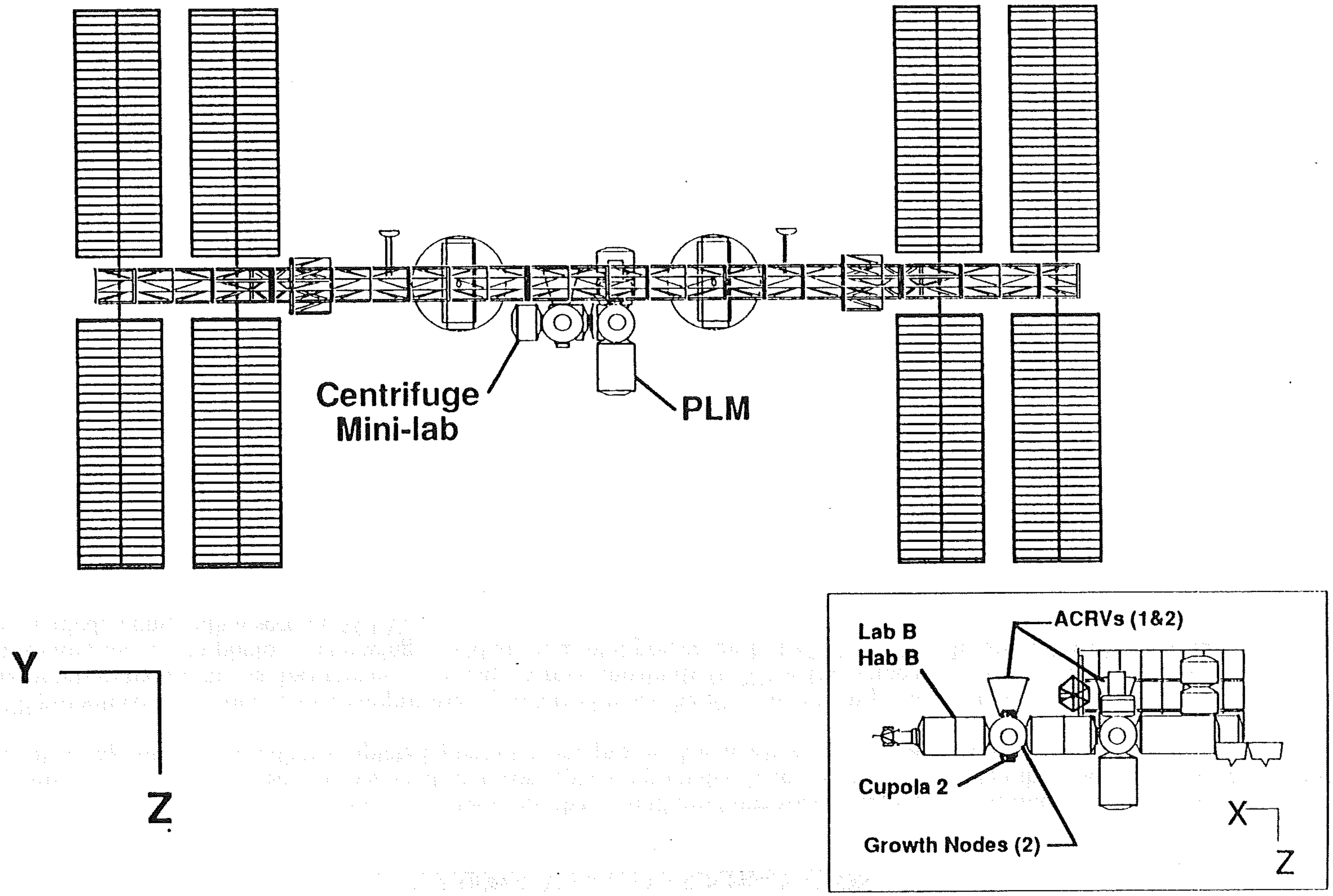
## EIGHT CREW CAPABILITY CONFIGURATION

As was discussed earlier, a preliminary set of SSF evolution phase configurations was developed to facilitate the completion of several systems trade studies. These four SSF evolution concepts are provided here. It should be noted that these are not necessarily the final set of configurations since the complete Figure of Merit process has not been applied at this time.

The first SSF growth configuration is more appropriately referred to as the SSF Follow-On phase as it is currently accounted for in the existing program requirements documents. This Eight Crew Capability (ECC) as the name implies, will accommodate a crew of eight. In addition, the fourth photo voltaic wing is added for a total power level of 75 kW. Also, the second habitat and laboratory modules are added, along with a second ACRV.

## Evolution Summary

# Eight Crew Capability (ECC)

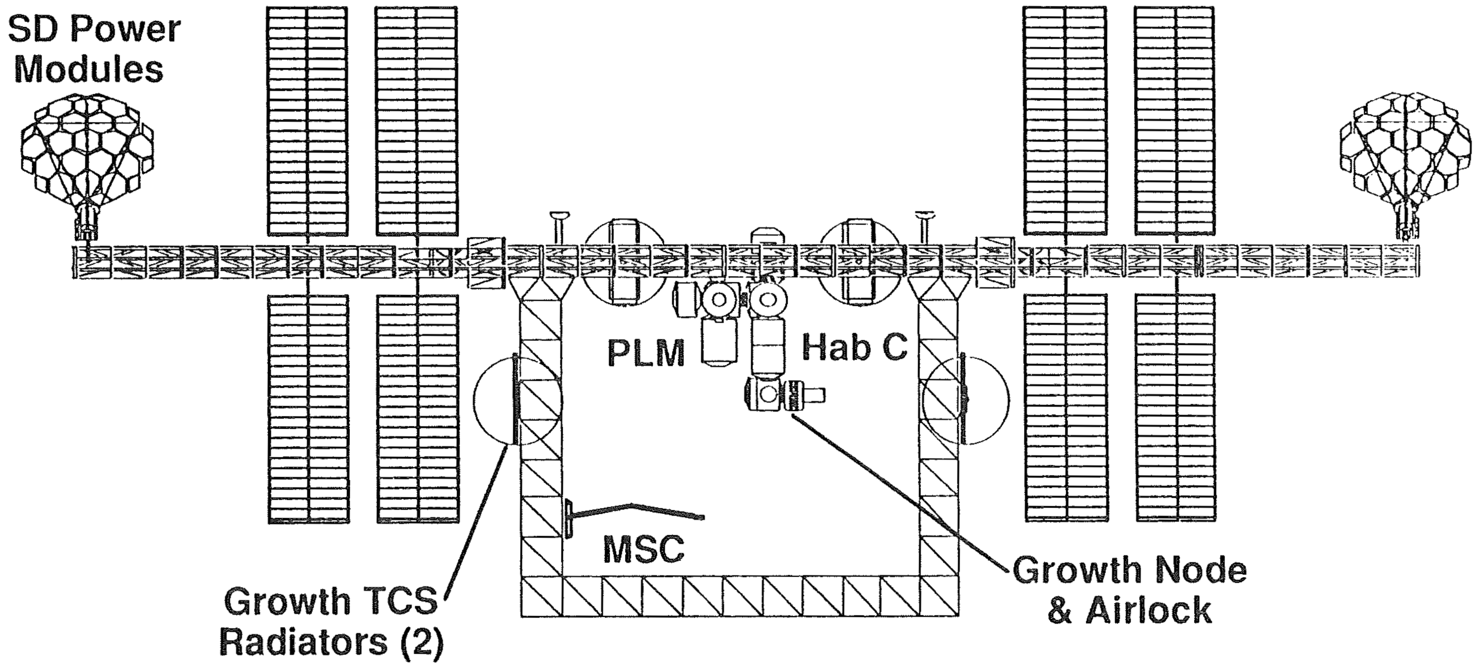


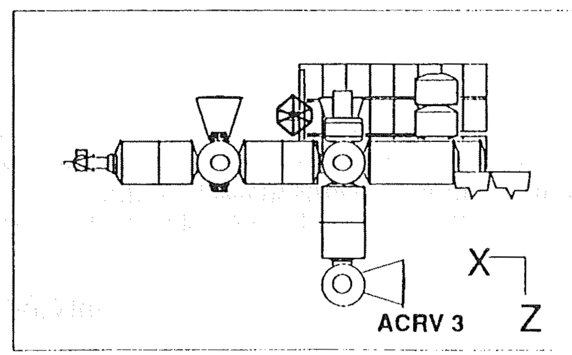
## INTERIM RESEARCH AND DEVELOPMENT CAPABILITY

The second evolution phase adds two solar dynamic power elements (each at 18.75 kw), one on either end of the transverse boom, along with another habitat module to accommodate growth in the crew requirements. In addition, growth structure in the form of lower keels and boom have been added to accommodate the growth radiators required to handle the increase in thermal rejection requirements. The keels and boom also allow for addition external mounting location for various science and technology payloads.

## Evolution Configuration and Concepts

# Interim Research & Development Capability



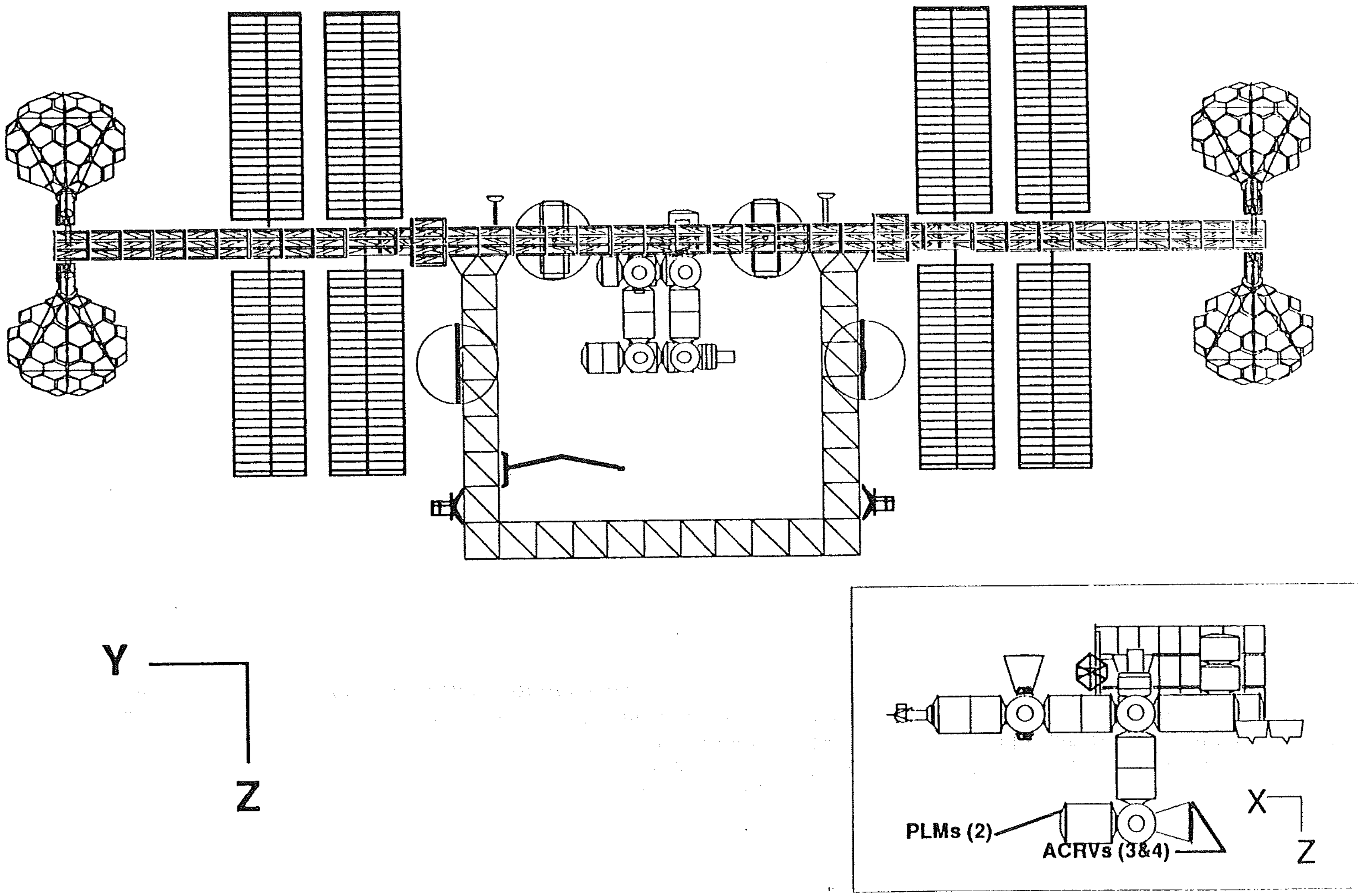



# ENHANCED OPERATIONS CAPABILITY

The Enhanced Operations Capability (EOC) configuration represents an implementation concept that fully accommodates projected multidisciplinary research and development user needs as they are currently understood. The EOC could accommodate a crew of up to sixteen with the addition of a fourth habitat module, along with a fourth ACRV. Two additional solar dynamic power modules are added, bringing the SSF total power level to 150 kW. At this time an advanced propulsion system with a higher efficiency is added on order to reduce SSF reboost propulsion requirements.

## Evolution Configuration and Concepts

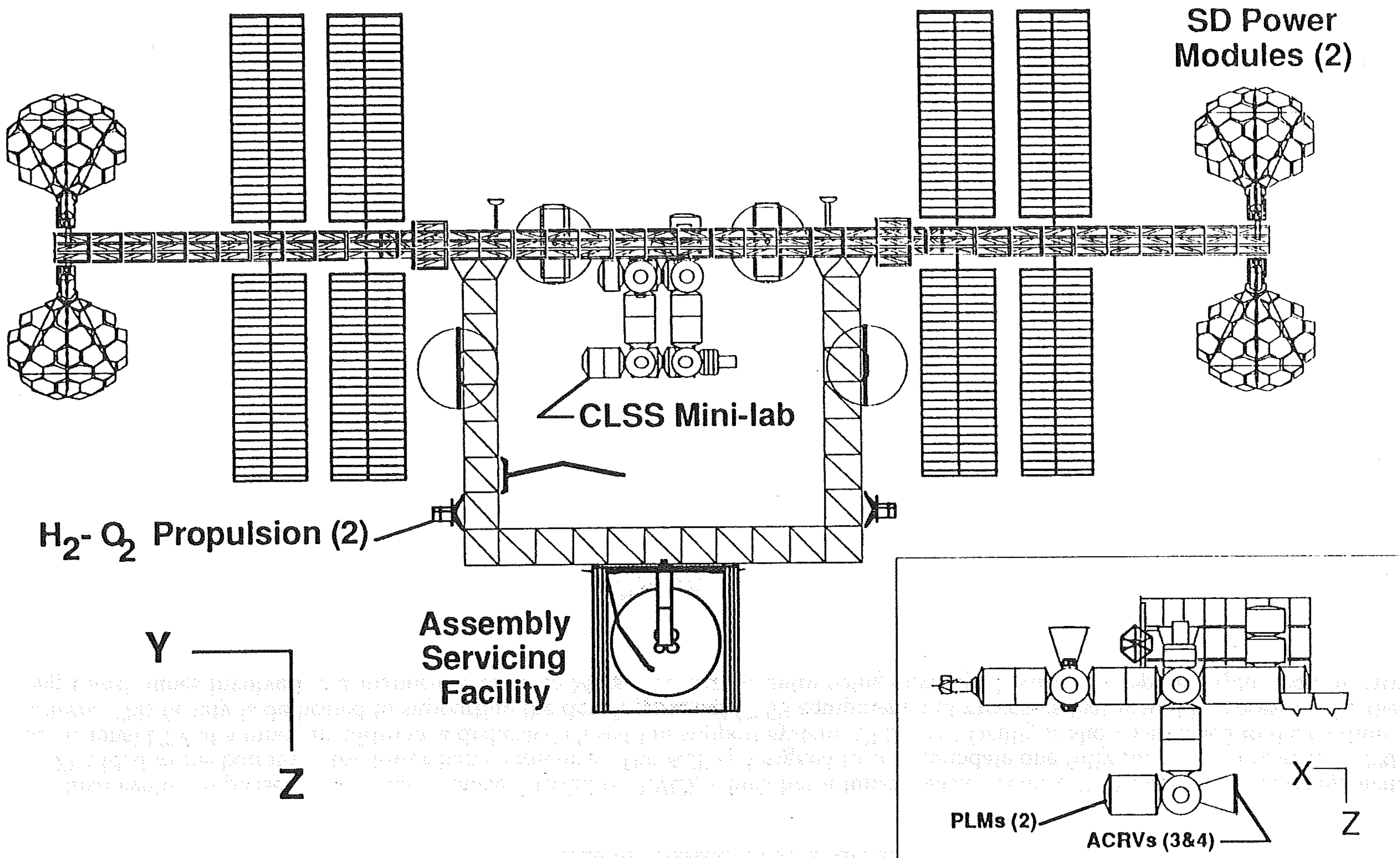
# Enhanced Operations Capability (EOC)

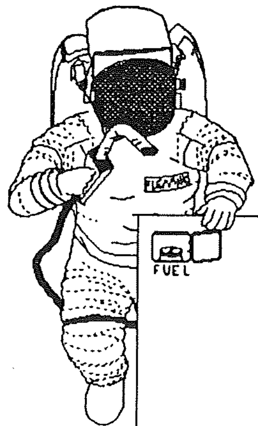


## LUNAR VEHICLE CAPABILITY

The final evolution phase is the Lunar Vehicle Capability (LVC), which has a lunar transfer vehicle (LTV) assembly servicing facility (ASF) added to the bottom of the lower boom structure. The ASF is designed to accommodate one fully fueled (approximately 200 metric tons) LTV at a time. In addition, a dedicated closed life support system (CLSS) test facility is shown attached to the module pattern. This facility is dedicated to supporting the development of CLSS equipment and processes that would be necessary for the long transit times involved in a manned mission to Mars that are currently being developed within the Space Exploration Initiative.

# Lunar Vehicle Capability (LVC)






# STV Fueling Options

**Space Station Evolution**
**Beyond the Baseline Conference**

**August 7, 1991**

**Ken Flemming**
**McDonnell Douglas Space Systems Company**

# Outline

- Introduction
- Operations Concepts for On-Orbit Propellant Management
- Lunar Vehicle Processing Times
- Assembly of Propellant Management Facility Concepts
- Maintenance of Propellant Management Facility Concepts
- Analysis of Early Shuttle ET Mating Problems
- Conclusions

# Introduction

Lunar vehicles that will be space-based and reusable will require resupply of propellants in orbit. Approximately 75% of the total mass delivered to low earth orbit will be propellants. Consequently, the propellant management techniques selected for Space Exploration Initiative (SEI) orbital operations will have a major influence on the overall SEI architecture.

# Introduction

- Approximately 3/4 of the total mass to low-earth orbit for lunar missions will be propellant.
- Propellant management techniques selected will have a major impact on the overall SEI architecture.
- There are two primary options for propellant resupply of Space Transfer Vehicles:
  - Replacement of depleted propellant tanks
  - Replenishment of depleted tanks
- Data presented was culled from three studies:
  - Fuel Systems Architecture Study
  - On-Orbit Assembly/Servicing Study
  - Aerobraked Lunar Vehicle Cost & Operations Assessment

# Key Technology Development Required

There are several technologies that will require further development to enable successful propellant management operations on orbit. These technologies are common to both drop tank installation and propellant transfer refueling options.

# Key Technology Development Required

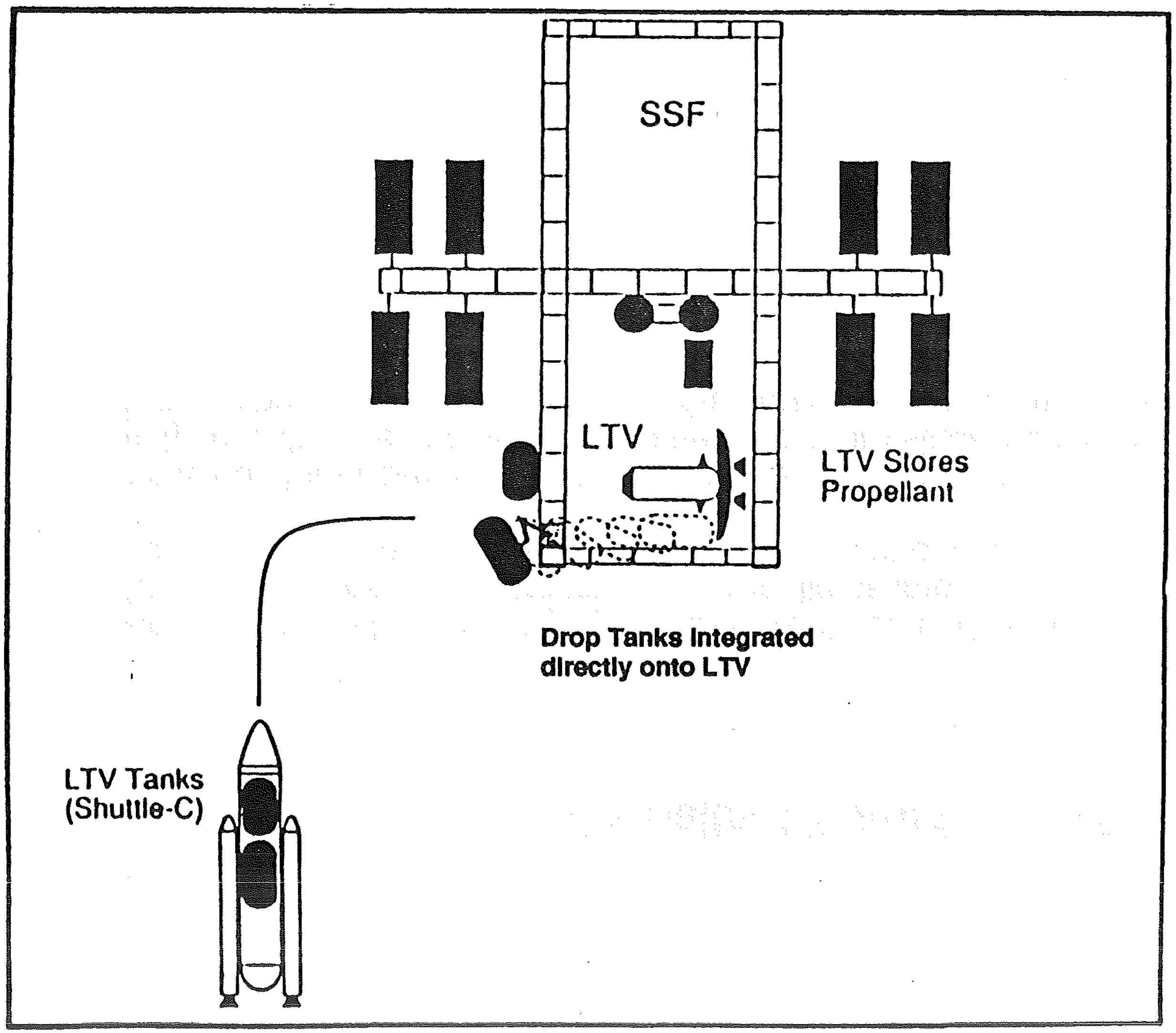
| Technology | Propellant Management Concept | |
|---|---|---|
| | Drop Tank | Propellant Xfer |
| Fluid Transfer | √ | √ |
| Leak Detection | √ | √ |
| Mass Gauging | √ | √ |
| Liquid Acquisition | √ | √ |
| Fluid Dynamics (slosh, settling, etc.) | √ | √ |
| Boiloff Control (VCS, reliquefaction, refrigeration, TVS, etc.) | √ | √ |
| Reliable Quick-Disconnect Fluid Interfaces | √ | √ |

- Key cryogenic technology developments are common to both methods of on-orbit propellant resupply.

# Drop Tank Installation

The Drop Tank Installation operations concept calls for refueling of the Lunar Transfer Vehicles (LTV) by replacement of the empty propellant tanks that will be jettisoned during the mission. Three Shuttle-C launches would be needed to deliver the entire propellant load (contained in four fully-loaded drop tanks) to the LTV. The drop tanks would be installed on the LTV at the SSF Assembly/Servicing Facility during vehicle turnaround processing.

# Drop Tank Installation




## Propellant Operations

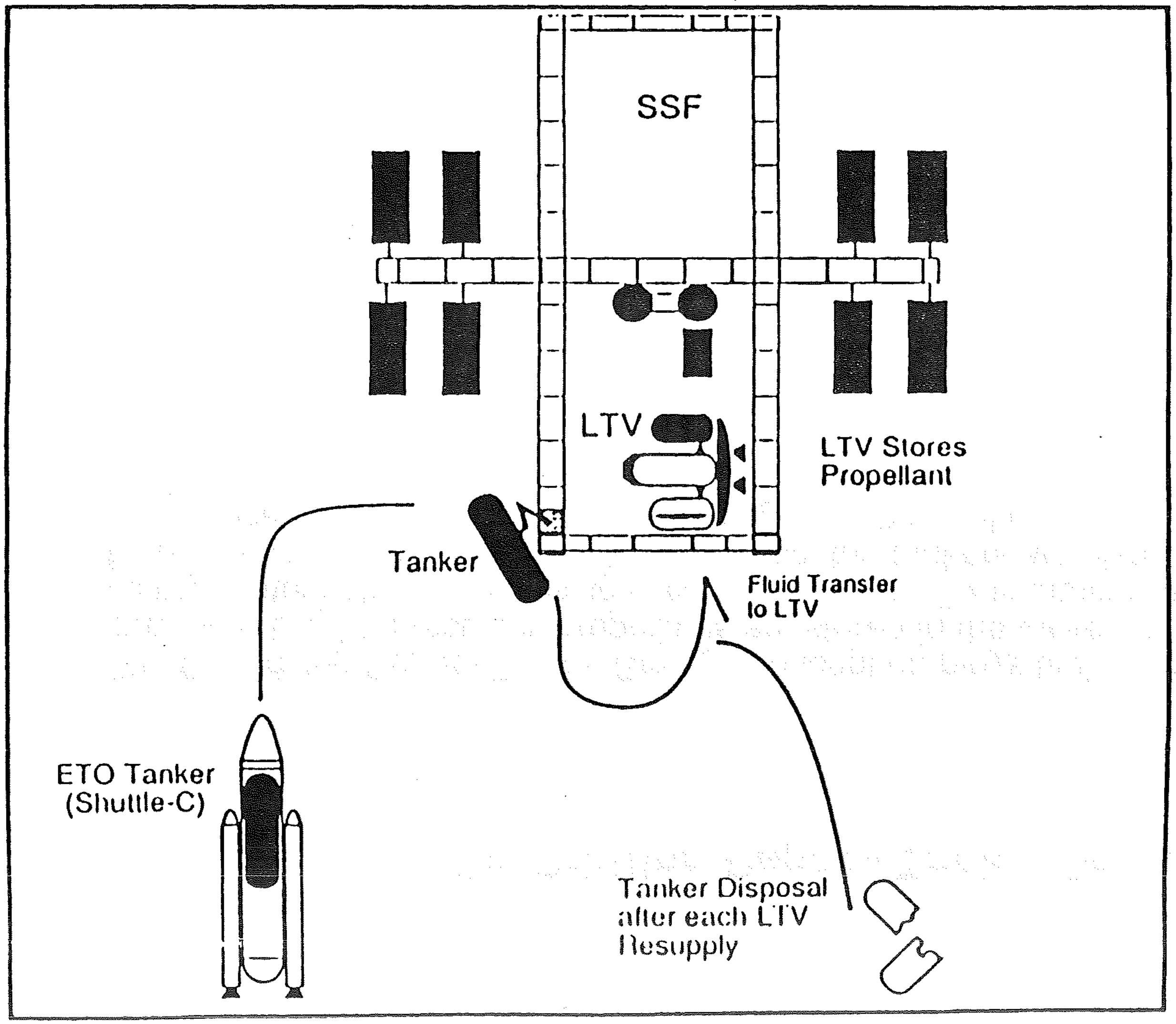
- LTV propellant drop tanks delivered to SSF via three Shuttle-C ETO launches.
- Drop tanks mated to LTV core immediately upon arrival at SSF.
- LTV core tanks resupplied from drop tanks prior to SSF departure.
- Two drop tanks jettisoned after TLI burn.
- LEV resupplied from LTV in low lunar orbit.
- Remaining two drop tanks jettisoned prior to TEI burn.
- Residual propellant boiloff control upon return to SSF.

# Propellant Transfer at SSF

Another method of resupplying the LTV would be to deliver the propellant to the Space Station in a tanker, then transfer the propellants into the LTV. In this operations concept the tankers are designed for short-term stays in orbit and are disposed of after use.

As is true for all propellant transfer from tankers concepts in this paper, the LTV tanks are fully reusable (i.e., not jettisoned after depletion) since launch of dry drop tanks increases the number of ETO launches, with the additional launch mass capability underutilized.

# Propellant Transfer at SSF



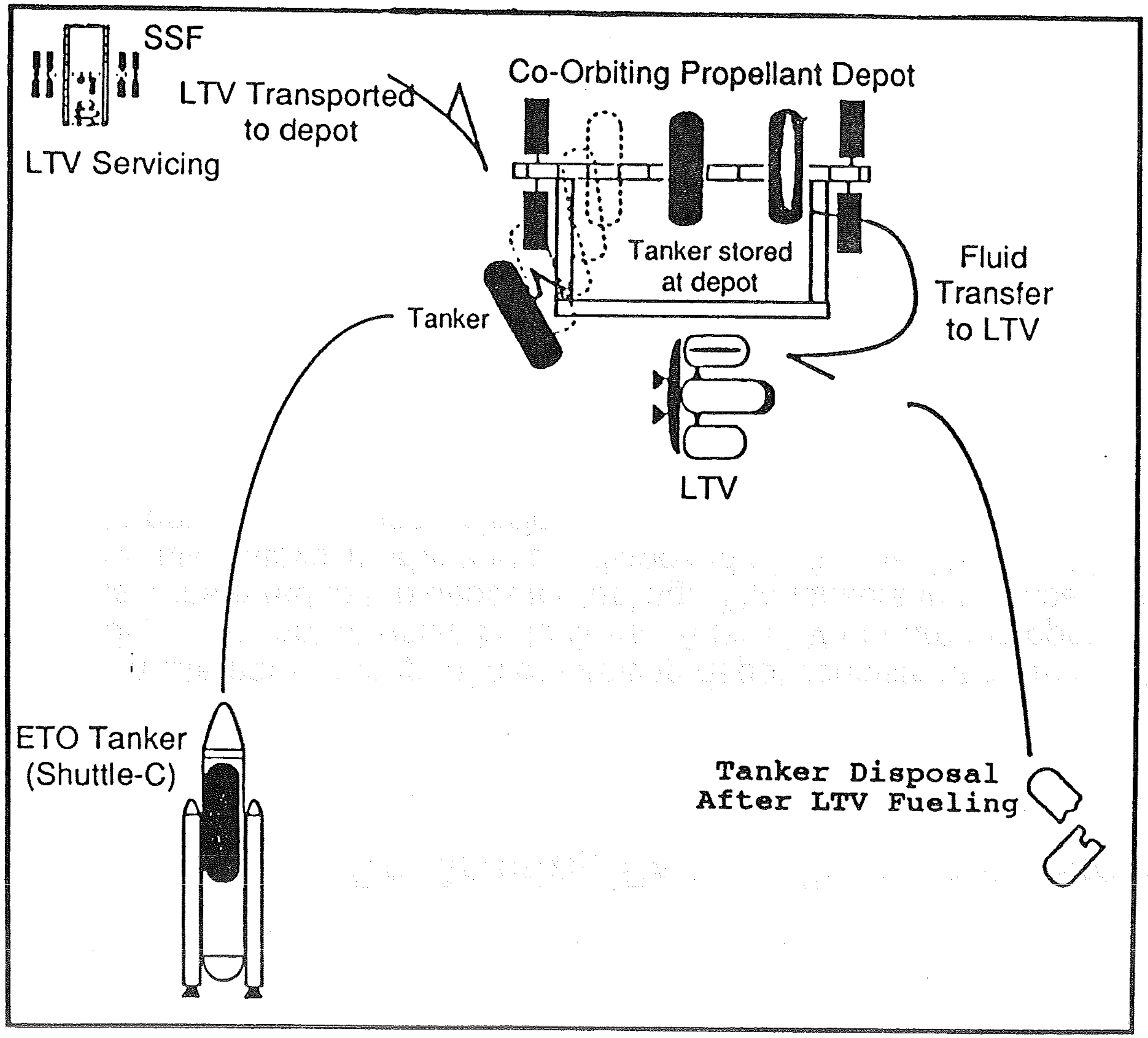

## Propellant Operations

- LTV umbilicals mated during vehicle checkout at SSF.
- Propellants delivered to SSF in three tankers via Shuttle-C ETO launches (one tanker per launch).
- Propellants transferred from tankers to LTV tanks upon arrival.
- Tankers deorbited after depletion.
- No jettison of LTV propellant tanks during mission.
- LEV propellants resupplied from LTV in low lunar orbit.
- Residual propellant boiloff control upon LTV return to SSF.

# Co-Orbiting Depot - Tanker Storage

The Co-Orbitng Depot - Tanker Storage concept employs tankers designed for long-term stays in orbit. The resupply propellants are stored in the tankers at a separate, co-orbiting facility. After vehicle processing is completed, the LTV is transferred to the depot and fueled. After vehicle departure for the moon, the tankers are disposed of in the atmosphere. This concept is most conducive to utilizing reusable tankers.

# Co-Orbiting Depot - Tanker Storage



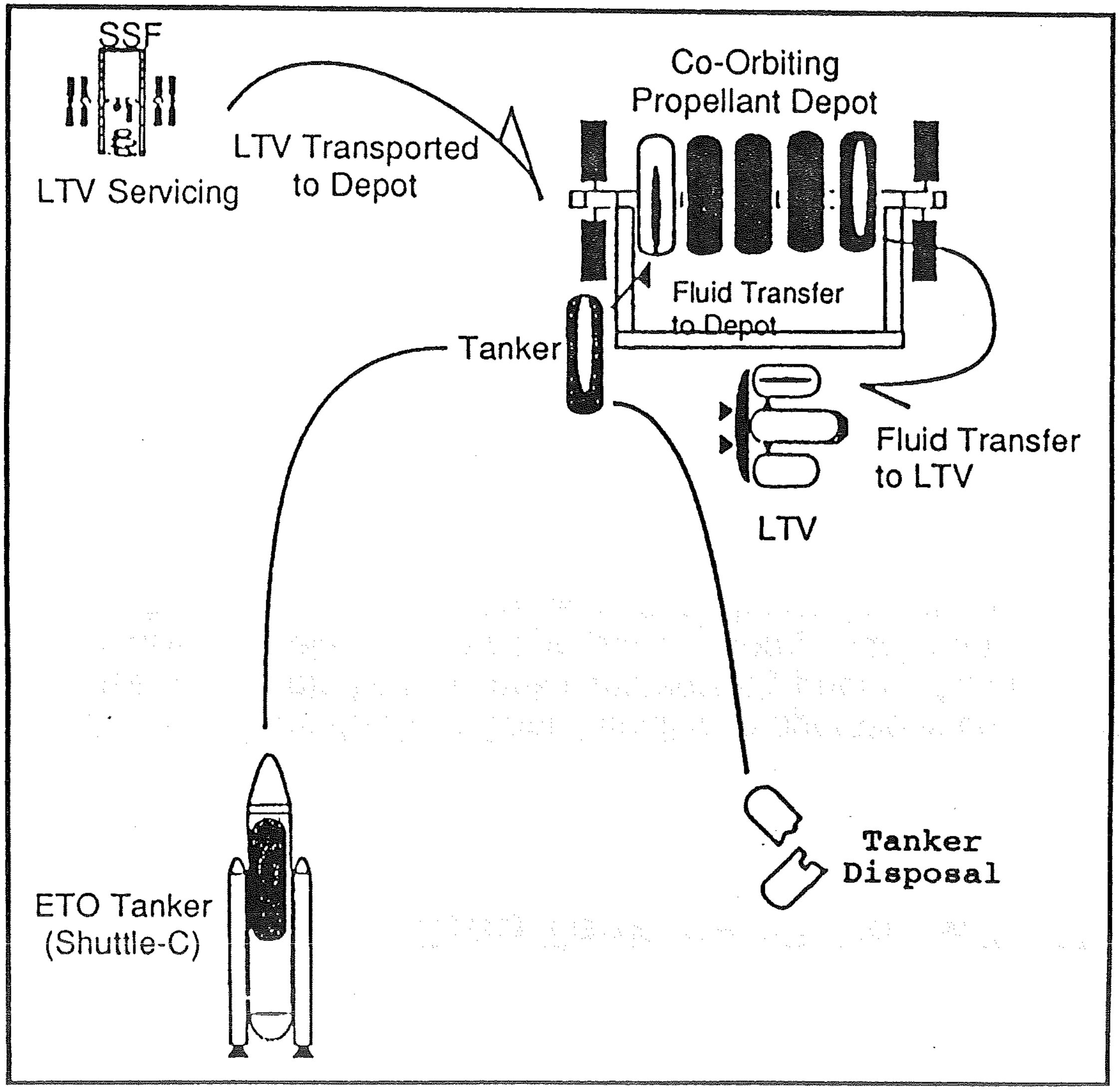

## Propellant Operations

- Propellants delivered to co-orbiting depot in three tankers via Shuttle-C ETO launches (one tanker per launch).
- Propellants stored at depot in tankers.
- LTV rendezvous and dock with depot after processing at SSF completed.
- Umbilicals mated and propellants transferred from tankers to LTV.
- Tankers deorbited after depletion.
- No jettison of LTV propellant tanks during mission.
- LEV resupplied from LTV in low lunar orbit.
- Residual propellant boiloff control upon LTV return to SSF.

# Co-Orbiting Depot - Permanent Storage Tank

An alternate concept of a co-orbiting depot consists of permanent storage tanks on the depot that are refueled by tankers. After LTV turnaround operations are finished, the vehicle is transferred to the depot for fueling. The tankers in this scenario are designed for short duration stays in orbit and are disposed of after depletion. This concept is the most tolerant to delays of the lunar mission.

# Co-Orbiting Depot - Permanent Storage Tank



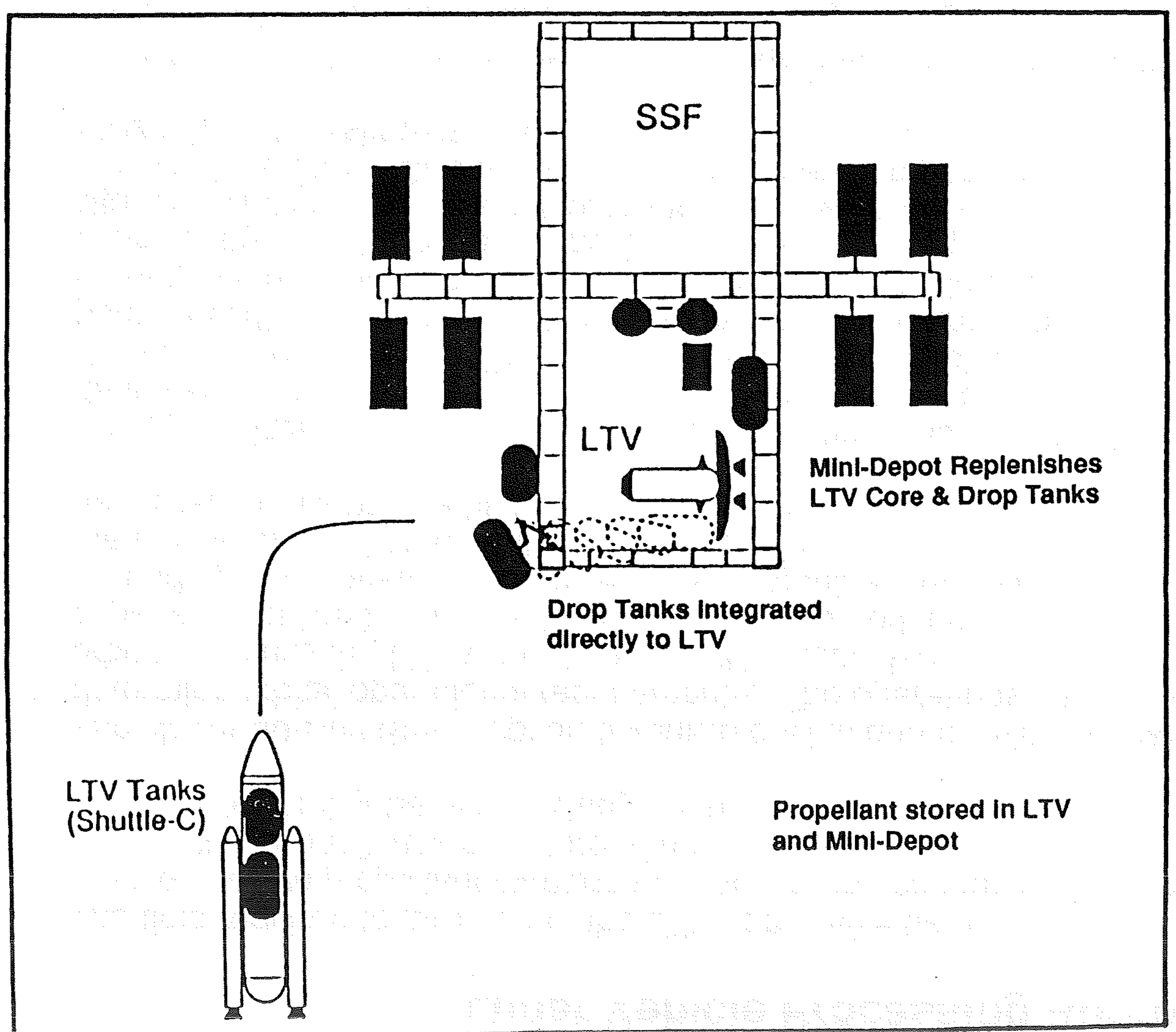

## Propellant Operations

- Propellants delivered to co-orbiting depot in three tankers via Shuttle-C.
- Propellants transferred from tankers to depot storage tanks upon arrival.
- Tankers deorbited after depletion.
- LTV rendezvous and dock with depot after processing at SSF completed.
- Umbilicals mated and propellants transferred from depot to LTV.
- No jettison of LTV propellant tanks during mission.
- LEV resupplied from LTV in low lunar orbit.
- Residual propellant boiloff control upon return to SSF.

# Drop Tank Installation with Mini-Depot

A variation on the Drop Tank Installation operations concept includes a "Mini-Depot" that is used to top-off the LTV tanks immediately prior to departure for the moon. The Mini-Depot consists of relatively small propellant storage tanks and transfer equipment that are used to fill the LTV core tanks and replace the boiloff losses experienced by the drop tanks.

# Drop Tank Installation with Mini-Depot




## Propellant Operations

- LTV propellant drop tanks delivered to SSF via three Shuttle-C launches.
- Drop tanks mated to LTV core immediately upon arrival at SSF.
- Mini-Depot resupplied.
- LTV core and drop tanks replenished by Mini-Depot prior to SSF departure.
- Two drop tanks jettisoned after TLI burn.
- LEV resupplied from LTV in low lunar orbit.
- Remaining two drop tanks jettisoned prior to TEI burn.
- Residual propellant boiloff control upon return to SSF.

# Lunar Vehicle Processing Approach

The time required to turnaround the LTV at the ASF between lunar missions was estimated for each of the five propellant management operations concepts. The estimates were based on the work of the Lunar Transfer Vehicle On-Orbit Processing Study performed by the MDSSC-KSC On-Orbit Assembly/Servicing Study Team.

The NASA 90-Day Study Option 5 vehicle design and mission scenario were first analyzed to determine orbital operational requirements. The operations that are expected to be required on orbit to process the LTV were determined by considering current and past vehicle processing experience at KSC. Many of the lunar vehicle on-orbit operations will be similar to current Shuttle ground ops. An operations concepts that organized the required tasks into a logical sequence was then developed. Only operations considered essential to process the LTV with the minimum effort necessary to maintain a high probability of mission success were included.

An appropriate analogy for each on-orbit operation was selected from the KSC ground operations database of procedures and schedules drawn from the Shuttle, Spacelab, Delta, Centaur, and Saturn/Apollo programs. The actual ground time of each analogy was determined, including only personnel directly involved with physically performing the task. A time estimate for the corresponding orbital operation was derived by "transitioning" the ground time to space, considering the differences of the SEI vehicle and manpower and resource limitations of the Space Station. The on-orbit time estimates for the operations were then compiled into a processing timeline flow chart. Operations were incorporated in parallel in the timelines when logical to fully utilize the refurbishment crew.

Adjustments to the timelines were then made based on EVA quantifiable analogies from Shuttle EVA and RMS operations and neutral buoyancy testing. Advanced automation capabilities were also considered and appropriate timeline modifications incorporated.

The final processing flow timeline was then modified for each of the five propellant management concepts in order to compare the impact on LTV processing times.

# Lunar Vehicle Processing Approach

Analyze Vehicle and Mission Scenario

↓

Develop Operations Concept

↓

Select & Quantify KSC Processing Analogies

↓

Transition Ground Tasks to On-Orbit Operations

↓

Assemble On-Orbit Processing Flows

↓

Incorporate EVA and Robotic Enhancements

↓

Modify Flows per PMF Concept

# Lunar Vehicle Processing Times

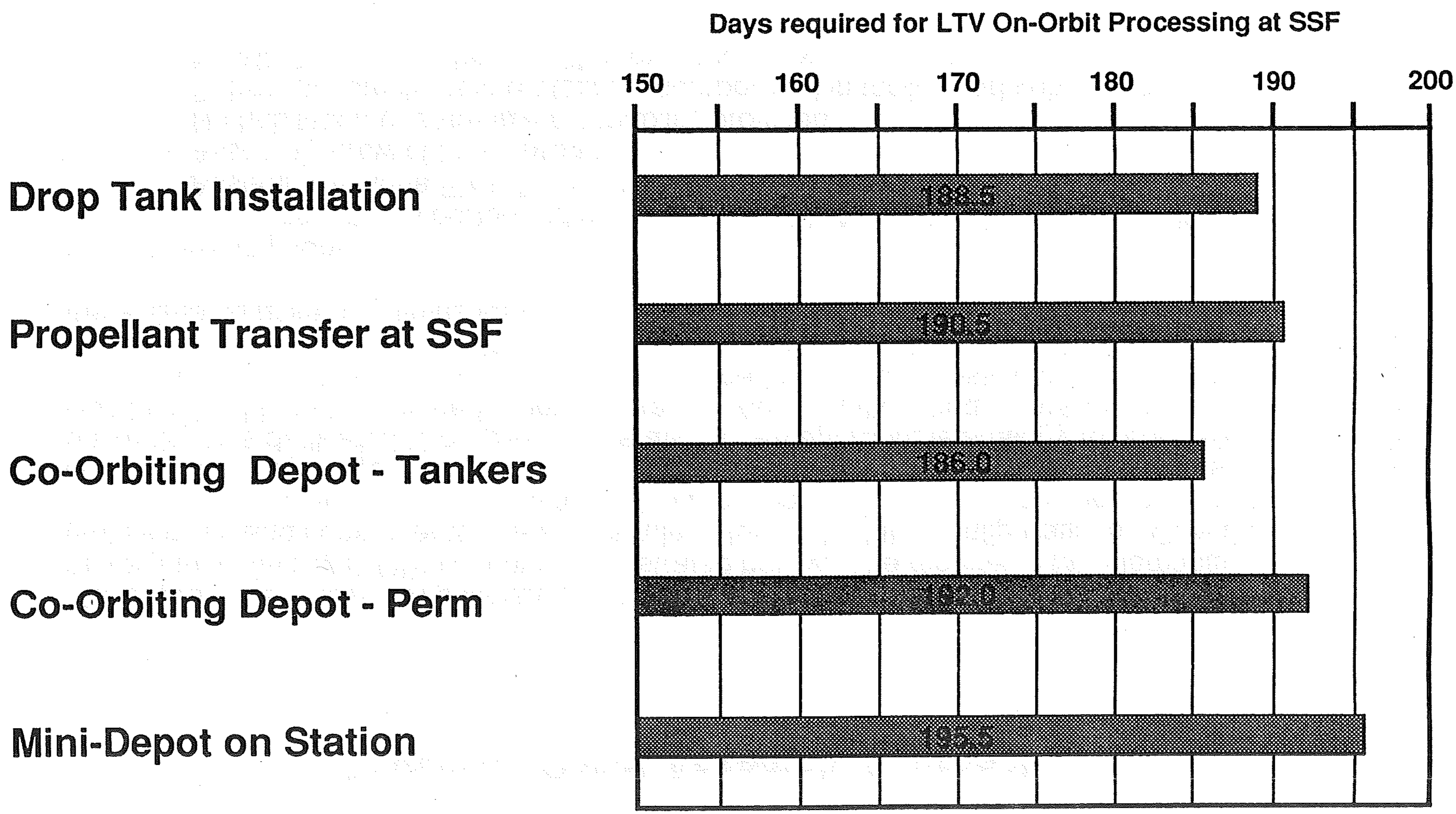
The comparison of the estimated LTV orbital turnaround processing times shows that there is no significant difference between the five propellant management architectures. The Drop Tank Installation method will require an estimated 188.5 shifts, with the other methods varying less than 4% from that baseline.

The propellant handling-specific operations constitute only 10 to 14% of the total LTV processing time. Based on the KSC analogies of Shuttle External Tank (ET) mate and ET propellant load, installation of drop tanks and propellant transfer from a tanker were both estimated to be two-shift operations. Also included in the timelines are tanker deorbit operations and Advanced Orbital Maneuvering Vehicle (AOMV) servicing.

Primary assumptions:

- LTV is the Option 5 vehicle from the NASA 90-Day Study
- SSF Assembly/Servicing Facility (ASF) is fully operational
- steady-state lunar missions
- AOMV operational and SSF-based
- dedicated orbital processing crew of four personnel
- Shuttle-C is the the Earth-to-orbit (ETO) carrier

# Lunar Vehicle Processing Times




- There is no significant difference between propellant management architectures for lunar vehicle processing time.

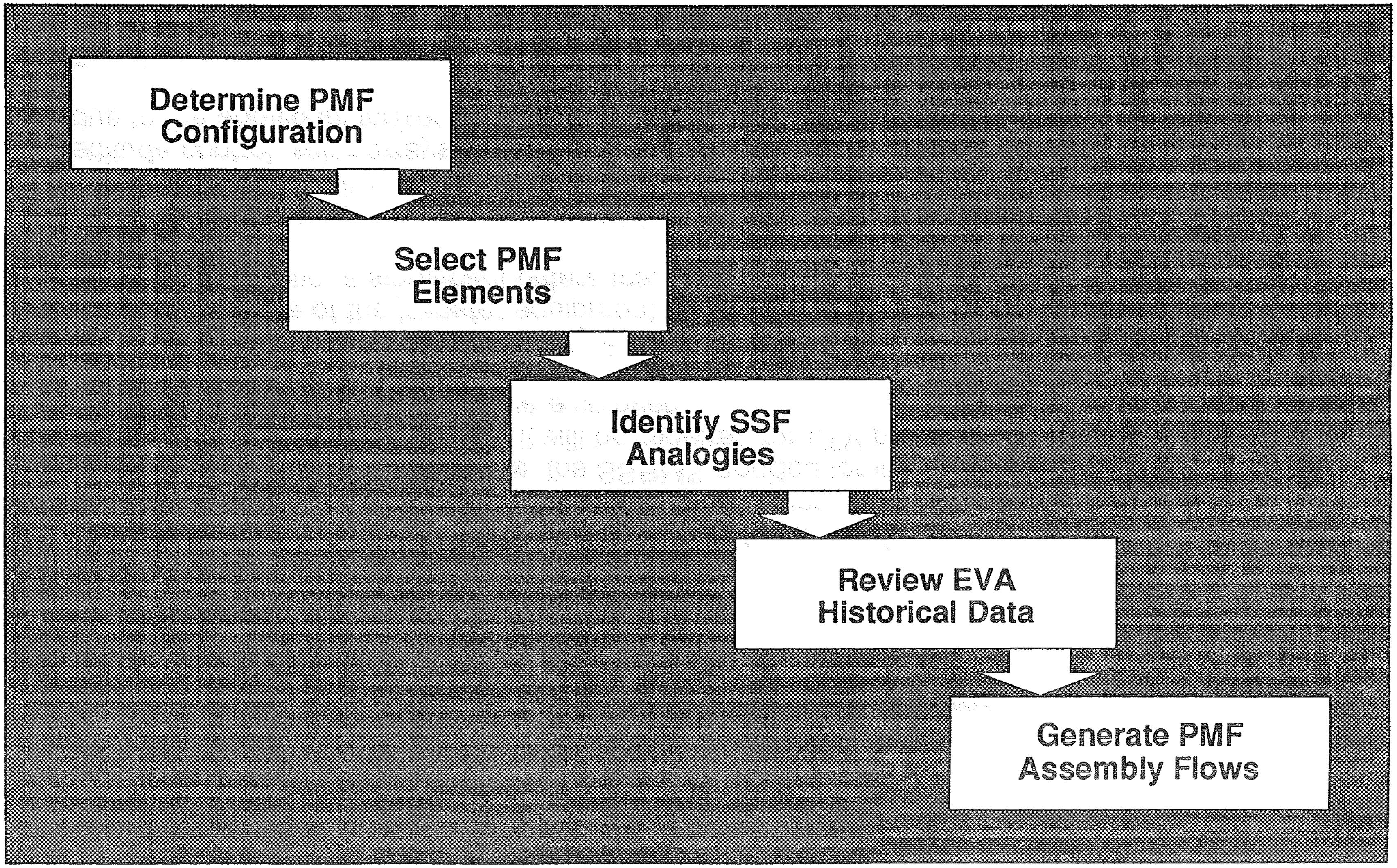
# Propellant Depot Assembly Approach

The approach employed to estimate the on-orbit assembly times for each of the propellant management facility (PMF) concepts is illustrated below. The required PMF elements (subsystems and components) were determined for each of the configurations. Only the orbital support equipment (OSE) dedicated to propellant handling was considered, however, all co-orbiting depot systems (i.e. support truss, attitude control, etc.) were included since the entire depot is dedicated to propellant operations. An appropriate analogy for each element was identified from the Space Station program. Additionally, Shuttle EVA experience such as the Solar Max repair and the Ease/Access experiment was investigated. The assembly time estimates for the Space Station and the EVA historical data were both used to generate the estimated assembly times for the five PMF concepts.

Primary assumptions:

- PMF assembly is performed at the growth SSF Assembly/Servicing Facility
- Assembly is done EVA, SSF-style (little or no automation)
- Assembly crew of four astronauts
- No habitation or safe-haven capability provided
- Debris/micrometeoroid protection incorporated in facility and vehicle designs
- No MSC/RMS required for PMF operations except drop tank installation

# Propellant Depot Assembly Approach



# Propellant Depot Assembly Times

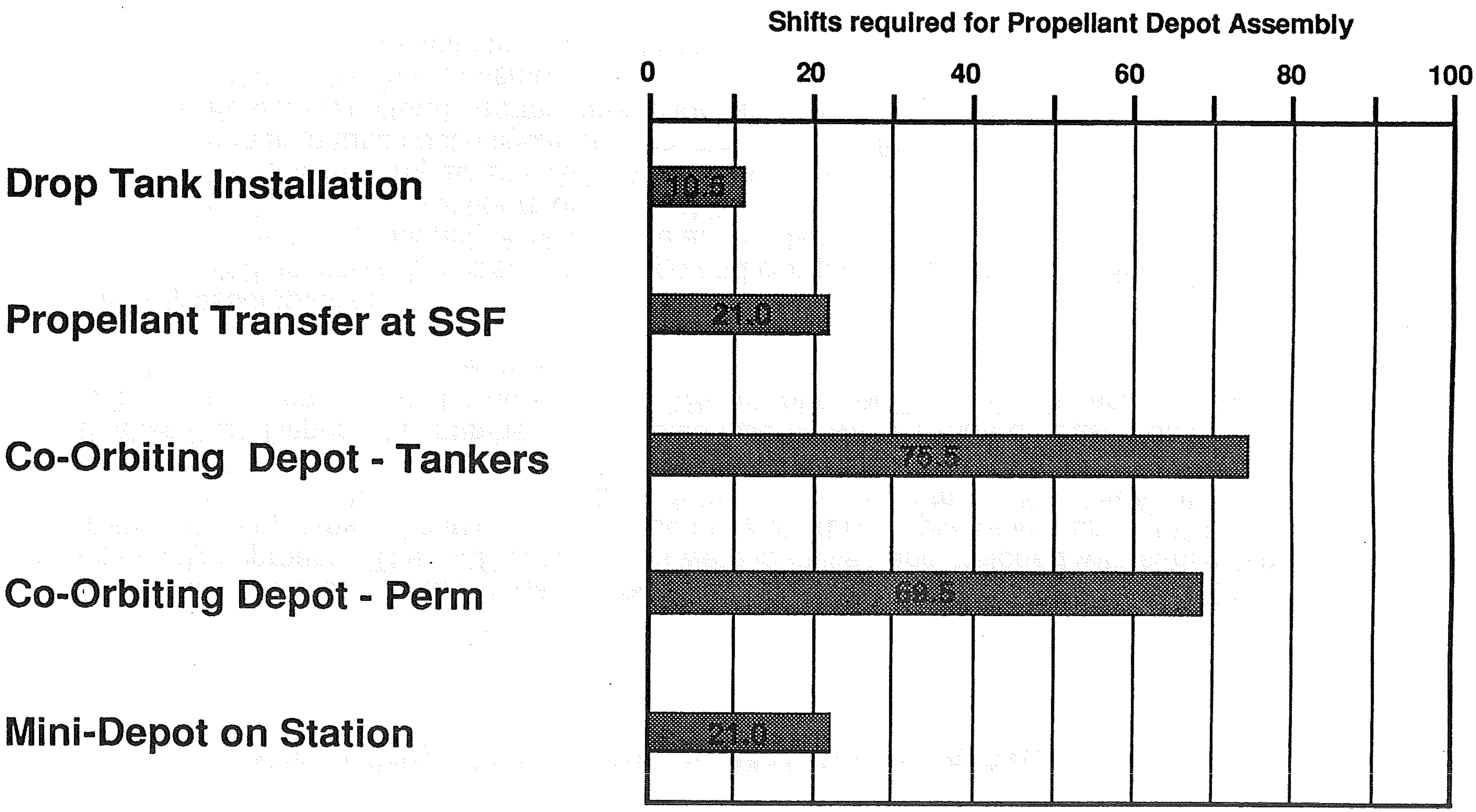
The comparison of the PMF estimated assembly times yielded expected results. Drop Tank Installation was the clear winner since it will require very little OSE that is dedicated to propellant handling. For instance, the SSRMS needed for installing the Drop Tanks was not included in the timeline because it will be required for LTV processing regardless of the propellant management technique employed.

The Propellant Transfer at SSF facility will take twice as long to assemble as the Drop Tank concept because of the transfer equipment needed. Relative to LTV processing time, however, this is not a significant difference.

Co-orbiting depots will require considerably more assembly time than the SSF-attached concepts, as they will need all the systems of a self-sufficient orbital node (support truss, attitude control, solar arrays, etc). Assembly of the Tanker Storage concept is slightly longer due to the additional tanker docking ports and associated transfer equipment.

The PMF assembly times are rough estimates and should be used only for comparison of the concepts.

# Propellant Depot Assembly Times




- Co-orbiting propellant depots require 200 - 600% more assembly shifts.
- Propellant Transfer depots require twice as many assy shifts as Drop Tank.

# Propellant Depot Annual Maintenance Approach

The estimation of annual maintenance requirements for the PMF concepts was similar to the assembly approach. The PMF subsystems were identified and matched with subsystems from other programs, primarily SSF. The quantity of orbital replacement units (ORU) components for each subsystem was then determined. Using the In-Service Analysis method of the Space Station Freedom External Maintenance Task Team Final Report (Fisher-Price Report), the number of predicted failures was estimated. Based on an average ORU replacement time of 1.1 hours and 5 ORU repairs per EVA shift, the estimated annual maintenance shifts were determined.

Primary assumptions:

- PMF is similar in subsystem design and component reliability to SSF
- Repairs are primarily EVA remove and replace
- EVA overhead = 2 hours per EVA shift
- Mean time to repair an ORU = 1.1 hours
- 5 maintenance actions can be accomplished per EVA shift
- Passive structural, thermal protection, and debris shielding ORUs not included in assessment
- Only corrective maintenance actions considered

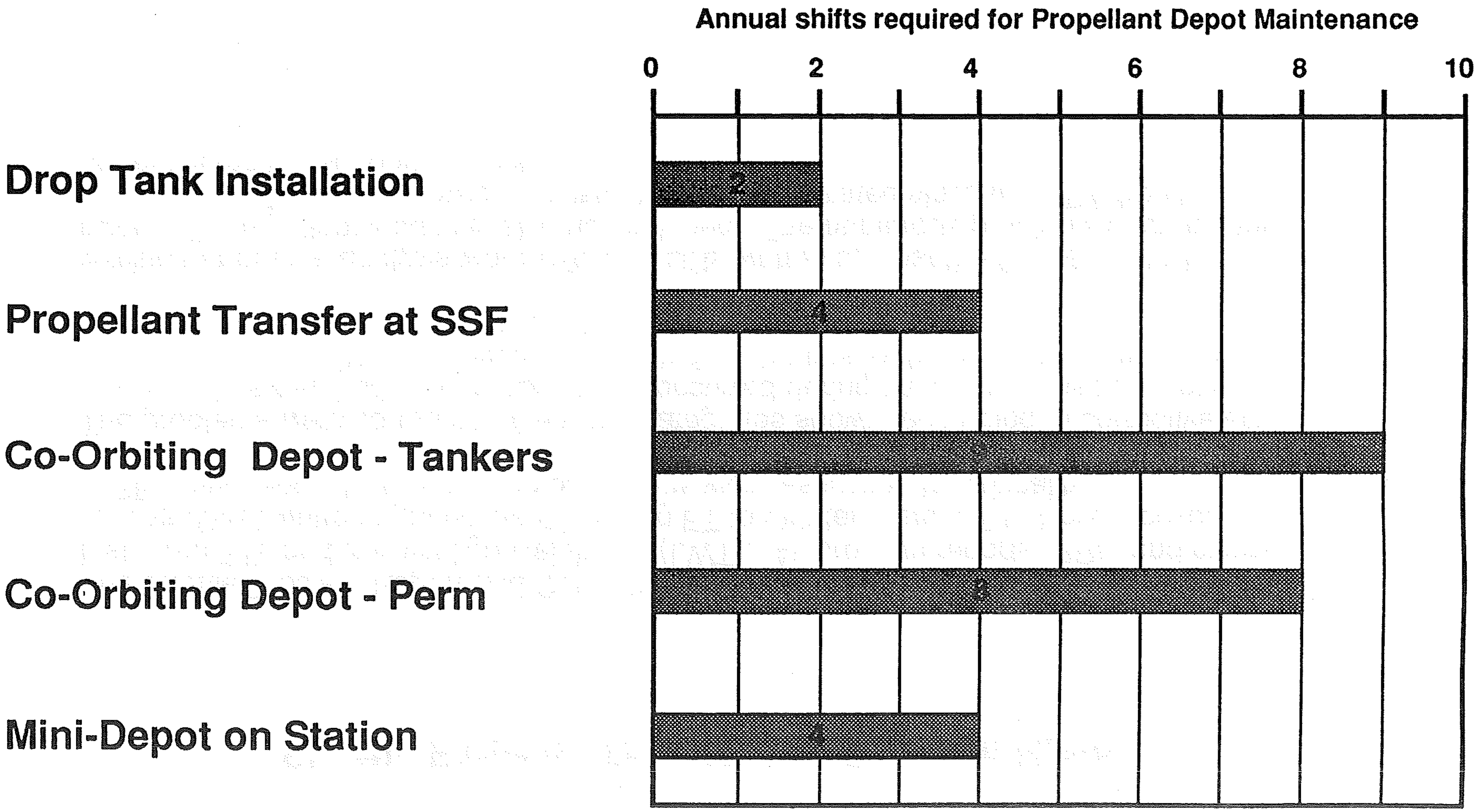
# Propellant Depot Annual Maintenance Approach

1. Determine PMF Configuration
2. Determine PMF Subsystem Reqmnts
3. Identify Analogies
4. Determine Quantity and Type of ORUs
5. Calculate Predicted Number of Failures
6. Calculate Annual Maintenance Shifts

# Propellant Depot Annual Maintenance

Comparison of the estimated annual maintenance requirements for the PMF concepts showed the Drop Tank Installation as a clear winner, needing only an estimated 2 shifts per year, with the Propellant Transfer and Mini-Depot facilities close behind at 4 shifts per year. The co-orbiting depots, however, increase the maintenance needs by 100 - 350%, which is quite significant in light of the remote location of the depot. The logistics infrastructure and readily available repair crew is a major benefit for SSF-attached PMF architectures. A co-orbiting depot could potentially require a dedicated Shuttle mission to repair a critical failure.

# Propellant Depot Annual Maintenance




- Co-orbiting propellant depots require 100 - 350% more annual maintenance.

# Shuttle External Tank Mating Problem History

The Shuttle Problem Report and Corrective Action (PRACA) database was examined for the first three ETs and the first lightweight ET (LWT). All problem reports (PRs) and discrepancy reports (DRs) written against the ET during ET to Orbiter mate, ET to Solid Rocket Booster (SRB) mate, and interface testing operations were assessed for criticality.

The problems were sorted into the three categories shown, according to corrective action that would be required if the problem had occurred during an on-orbit assembly of drop tanks to the LTV. Problems were also sorted by the type of hardware system affected: electrical, fluids/pneumatics, or structures.

Excluded from the analysis were PRs and DRs written against the Orbiter and SRBs during mate. ET propellant load was also not included. The numerous problems documented against the ET thermal protection system were also omitted since the LTV drop tanks are not expected to use foam insulation.

# Shuttle External Tank Mating Problem History

- Examined External Tank records from ET-1, 2, 3, and LWT ET-8 for ET-Orbiter-SRB mate problems

- Sorted all problem/discrepancy reports into three STV related categories:
  1 - Would require replacement hardware from earth
  2 - Repairable on-orbit, but with schedule impact
  3 - Not a significant on-orbit concern

- Sorted all problem/discrepancy reports into three system related categories:
  Electrical
  Fluids/Pneumatics
  Structures

# ET Mate Problem Categories

Examples of the types of problems in the three categories are shown.

# ET Mate Problem Categories

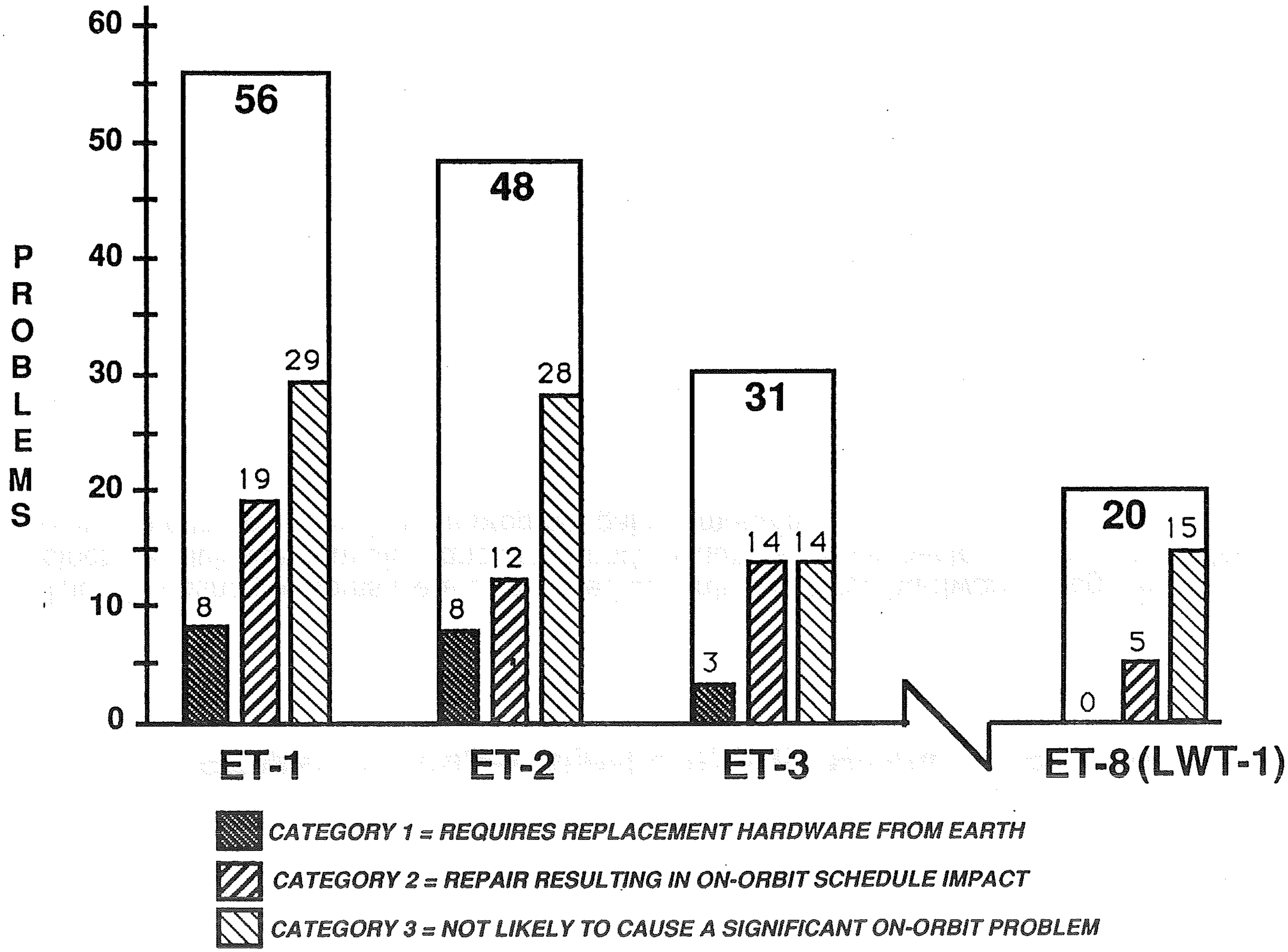
| Category 1&2 | | Category 3 |
|---|---|---|
| Broken/Crushed Wires | Missing Hardware | External Tank Unique Hardware |
| Electrical Shorts | Structural Interferences | Tasks Not Done On-Orbit |
| Cables To Short To Mate | Loose Fasteners | Procedural Errors |
| Broken Sensors | Damaged Fasteners | Cosmetic Defects |
| Loose Electrical Connections | Missing/Broken Safety Wire | Out-of Tolerance Readings |
| Leaking Fluid Lines | Incorrect Shimming | Incorrect Part Identification |
| Scratched Cryogenic Seals | Corrosion | |
| Bent Fluid Lines | Foreign Material/Debris | |
| Failed Valves | Misalignment of Hardware | |

# ET Mate Problem Distribution by Criticality

The problems documented during ET mate for the first three and the eighth (LWT-1) Shuttle flights were categorized according to criticality. There were a high number of problems associated with the early assembly operations. As expected, the number of problems decreased with each succeeding mission processing flow as hardware design, manufacturing, and operations matured.

ET mate is a complex assembly operation; drop tank installation is a similarly complex operation that will occur four times per mission. The alarming number of Category 1 problems experienced during the first three Shuttle ET mates would cause unacceptable delays in lunar missions if experienced in orbit.

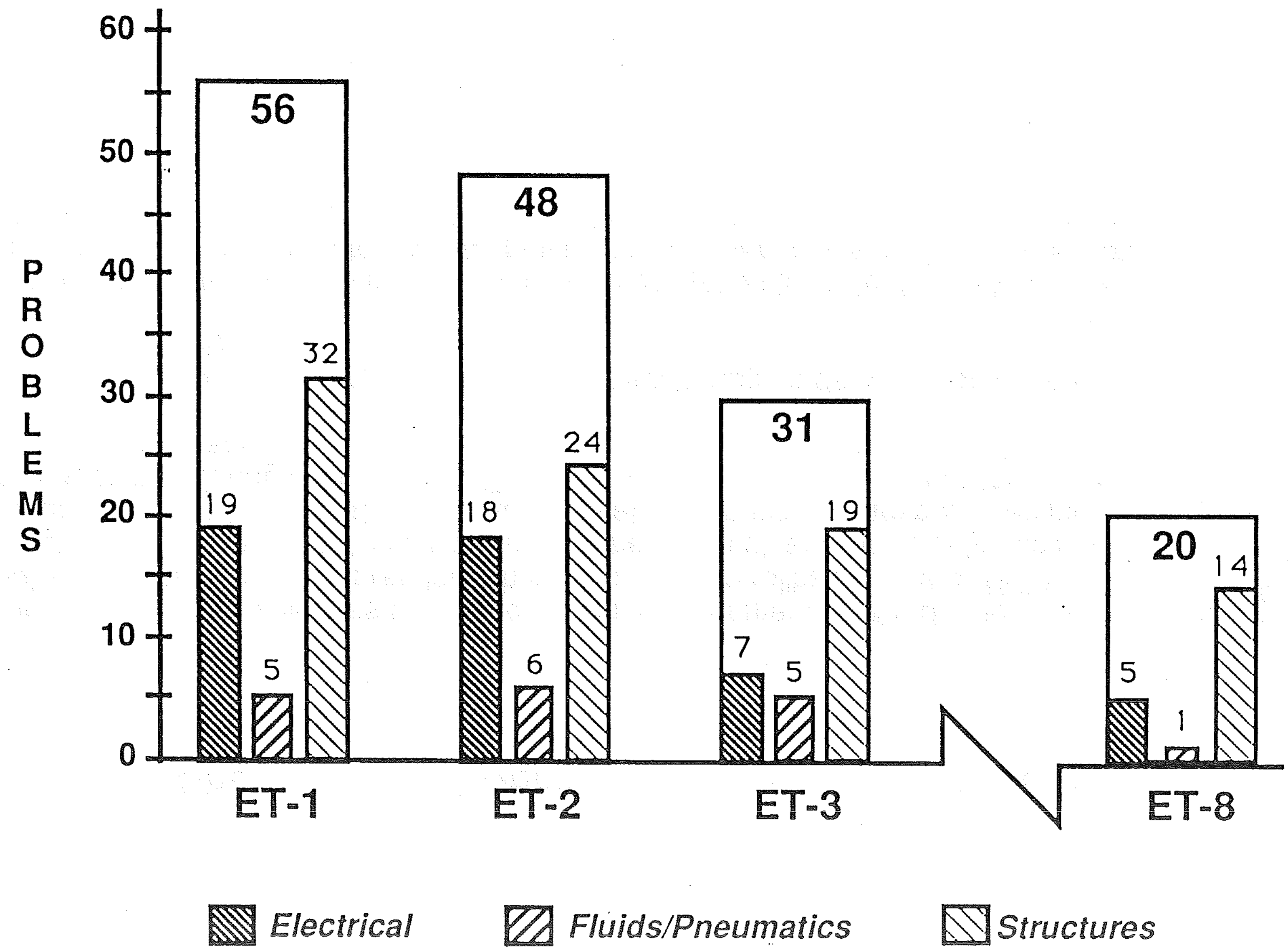
# ET Mate Problem Distribution by Criticality



# ET Mate Problem Distribution by Hardware System

The ET mating problems were also sorted according to three hardware categories: electrical, fluids/pneumatics, and structural/mechanical. As expected, all systems reflected a downward trend as the Shuttle program gained maturity.

# ET Mate Problem Distribution by Hardware System



# Shuttle ET Hydrogen Disconnect Leak Lessons

The Space Shuttle fleet was grounded during the summer of 1990 due to a series of hydrogen leaks. The leaks caused three launch scrubs and two rollbacks to the VAB for ET demate from the Orbiter. These "smart" leaks were extremely difficult to isolate, only occurring at cryogenic temperatures and with inert purges and insulation serving as transport mechanisms to give false readings during leak checks. Extensive disassembly and vendor testing were required to isolate the leak sources.

It is especially disconcerting that problems of such magnitude would be experienced on a mature launch system.

The main recommendations from the leak investigation team for future launch systems were: 1) make designs as leak tolerant as possible (redundant seals, built-in purges, etc.), 2) eliminate as many joints as possible, and 3) design built-in, automated leak check methods.

# Shuttle ET Hydrogen Disconnect Leak Lessons

- Shuttle fleet grounded during summer of 1990 due to hydrogen leaks (3 launch scrubs and 2 rollbacks)
  - STS-35 (Columbia) delayed 5 months
  - STS-38 (Atlantis) delayed 4 months
- "Smart" leaks were extremely difficult to isolate.
  - Leaks occurred in cryogenic conditions only.
  - Extensive disassembly & vendor testing required to isolate leaks.
  - All leaks discovered on single-seal joints.
- Recommendations
  - Make designs as leak-tolerant as possible.
  - Eliminate joints as much as possible.
  - Design built-in, automated leak-check methods.

## Comparison of Propellant Interface Disturbances

The increased mission risk inherent with the use of drop tanks is a significant concern. The in-flight jettison and subsequent installation of four drop tanks per mission over the course of a five mission vehicle lifetime will result in a minimum of 160 cryogenic propellant interface disturbances per vehicle. In comparison, a LTV utilizing permanent, reusable propellant tankage will experience only 40 such disturbances.

The use of drop tanks greatly increases the number of failure modes and critical items. Cryogenic quick-disconnect couplings have a history of leakage, and isolation and repair of cryogenic leaks at KSC have proven at times to be an operational nightmare. Complex assembly operations by their very nature incur problems requiring parts rework or replacement. Such problems may prove to be insurmountable to processing crews in space.

The question remains to be satisfactorily addressed: Is the mass savings gained by jettisoning depleted propellant tanks in flight justify the increase in mission risk?

# Comparison of Propellant Interface Disturbances

## Drop Tank Installation

$$4\ \frac{\text{Drop Tanks}}{\text{Vehicle}} \times 4\ \frac{\text{Prop Interfaces}}{\text{Drop Tank}} \times 2\ \frac{\text{Disturbances}}{\text{Mission}} \times 5\ \text{Missions}$$

$$= 160\ \frac{\text{Disturbances}}{\text{Vehicle Life Cycle}}$$

## Propellant Transfer

$$1\ \frac{\text{Tankset}}{\text{Vehicle}} \times 4\ \frac{\text{Prop Interfaces}}{\text{Tankset}} \times 2\ \frac{\text{Disturbances}}{\text{Mission}} \times 5\ \text{Missions}$$

$$= 40\ \frac{\text{Disturbances}}{\text{Vehicle Life Cycle}}$$

- Use of Drop Tanks significantly increases number of critical propellant interface disturbances.
- An open question: Does the mass saved by jettisoning depleted propellant tanks justify the increase in mission risk?

# Conclusions

Five proposed propellant management facility (PMF) concepts were analyzed and compared in order to determine the best method of resupplying reusable, space-based Lunar Transfer Vehicles (LTVs).

**LTV Processing** - The processing time needed at the Space Station to prepare an LTV for its next lunar mission was estimated for each of the PMF concepts. The somewhat surprising result was that there is little difference in the estimated processing timelines among the concepts. The estimates vary less than 4% from the Drop Tank baseline of 188.5 shifts. The shortest estimate of 186.0 shifts was for the Co-Orbiting Depot - Tanker Storage facility.

**PMF Assembly** - The estimated times required to assemble and maintain the different PMF concepts were also compared. The distinguishing factor between the concepts is the orbital location of the facility. Co-orbiting depots will require significantly more time (200-600%) to assemble than the SSF-attached architectures. However, even the longest assembly time (75.5 shifts for the Co-Orbiting Depot - Tanker Storage) constitutes less than 10% of the total processing time for one LTV's life cycle of five missions.

**PMF Maintenance** - The results of the maintenance analysis were similar, with co-orbiting depots needing 100-350% more annual maintenance. The Drop Tank and Mini-Depot concepts were estimated to need only 2 shifts per year, whereas the co-orbiting depots required 8-9 shifts. This is quite significant in light of the remote location of a co-orbiting depot. The logistics infrastructure and readily available repair crew is a major benefit for SSF-attached PMF architectures. A co-orbiting depot could potentially require a dedicated Shuttle mission to repair a critical failure.

**Shuttle ET Mating History** - The first few ET mating operations at KSC encountered numerous problems that would, if experienced on orbit during Drop Tank Installation, cause serious lunar mission schedule delays. The grounding of the Shuttle fleet in the summer of 1990 due to hydrogen leaks at the ET disconnect is especially disturbing in that it occurred on a mature launch system. Ground processing methods to prevent such flight hardware problems must be developed to enable space-basing of LTVs.

**The Problem with Drop Tank Installation** - The use of Drop Tanks on lunar vehicles increases by a factor of four the number of critical propellant interface disturbances. The increased mission risk (many more failure modes and critical items, as well as the lkelihood of interface damage and requisite repair) must be satisfactorily addressed before being baselined into LTV designs.

**Key Technologies** - The key cryogenic propellant management technologies that require further development are common to all proposed architectures, and therefore are not a discriminator between the concepts. The development of these enabling technologies should be pursued aggressively.

# Conclusions

- There is no significant difference between PMF concepts for LTV on-orbit processing times.
- Orbital location is the cost and schedule driver for PMF assembly and maintenance.
- Shuttle - ET mating history shows an alarming number of problems that would cause LTV mission delays if encountered on orbit.
- Drop Tanks Installation requires four times as many critical propellant interface disturbances.
- Development of key orbital cryogenic propellant management technologies is required for all PMF concepts.

# Space Station Freedom/ Lunar Transfer Vehicle Propellant Operation Hazard Analysis

Sam Dominick (Presenter)
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International Corporation

# SSF/LTV Propellant Operation Hazard Analysis

Space Station Freedom (SSF), as a transportation node for Space Exploration Initiative missions, would involve the assembly and refurbishing of lunar and Mars transfer vehicles. This includes operations involving cryogenic propellants (LH2 & LO2) such as storing and handling of loaded propellant tanks, assembly onto the vehicle, and propellant transfer. Cryogenic propellants dictate rigorous safety precautions and impose unique requirements to ensure safety to both personnel and SSF elements. The objective of this study is to identify potential hazards and risks associated with cryogenic propellants. This involves identification of pertinent system design features and operational procedures. Criticality of identified risks/hazards shall be assessed and those that fall in the catastrophic and critical categories shall include mitigating solutions.

# SSF/LTV Propellant Operation Hazard Analysis

- Hazard Analysis Conducted To Define Hazards And Risks Of Storing, Handling And Transferring Cryogenic Propellants At SSF To Support LTV

- Objective:
  - Identify Hazard And Risk - Hardware, Operations, Human Error
  - Assess Criticality
  - Propose Mitigating Solutions

## SSF/LTV Propellant Operation Hazard Analysis (Cont.)

**Approach**

The initial approach to the hazard analysis consisted of selecting a baseline Lunar Transfer Vehicle (LTV) design from previous LTV studies. This reference vehicle provided a point of departure concept and was used to generate a detailed operational scenario. Included in the operational scenario are activities such as propellant refueling, storage, mission refurbishment, safing and propellant topoff of the drop tanksets. Hazards identified from these activities are then analyzed to provide mitigating measures in order to either eliminate them or reduce the risks to an acceptable level.

# SSF/LTV Propellant Operation Hazard Analysis (Cont.)

- **Approach:**
  - **Hazard Assessment Based On Selected Reference Scenario From LTV Design Studies**
  - **Assume Propellant Mini-Depot For Propellant Topoff And Contingency Supply**
  - **Develop/Assess Timelines And Scenarios For Propellant Refueling And Storage**
  - **Propose Measures To Mitigate Risks Of Identified Hazards - Assess Probability Of Occurrence For Hazards Without Suitable Solutions**





C-3

<u>**Task Plan**</u>

The SSF/LTV propellant operation hazard analysis is subdivided into four subtasks. The first subtask involves historical review of documentation pertinent to safety of cryogenic systems in space. The information derived from this effort provides an initial starting point and information base for the subsequent tasks. Subtask 2 examines risks and hazards associated with propellant refueling operations in reference to conditions producing the hazards and the severity of the impact on SSF. Subtask 3 is similar to subtask 2 except that it investigates vehicle operations other than refueling. These operations include vehicle turnaround operations, docking/storage, safing and various maintenance operations. Subtask 4 provides mitigating solutions to risk and hazards identified in both subtask 2 and 3.

Subtask milestones are listed below. The completion of the propellant operation hazard analysis is scheduled by August 9, 1991. The final report , written in "white paper" form, will be submitted by September 6, 1991.

# SSF/LTV Propellant Operation Hazard Analysis

## Task Plan

- Subtask 1 - Historical Review
- Subtask 2 - Cryogenic Transportation Refueling Risks
- Subtask 3 - Vehicle Operation Risks
- Subtask 4 - Mitigating Solutions

## Schedule Milestone:

Subtask 1 - Ongoing

Subtask 2 - Completed 9 July 1991

Subtask 3 - Completed 2 August 1991

Subtask 4 - Underway -- Complete By 9 August 1991

Final Report - 6 September 1991

## LTV Configuration

The LTV configuration baseline for the cryogenic propellant operation hazard study is shown below. This configuration provides a reference concept that is used as starting point for the analysis. Basic elements of the LTV are the crew & cargo modules, 6 drop tanksets and aerobrake assembly which are all attached to the common propulsion/avionics core. This vehicle can deliver 14.6 tonnes of cargo including a crew of 4 to the Lunar surface and return to the SSF using 174 tonnes of cryogenic propellant. Total vehicle dry mass is 27.5 tonnes.

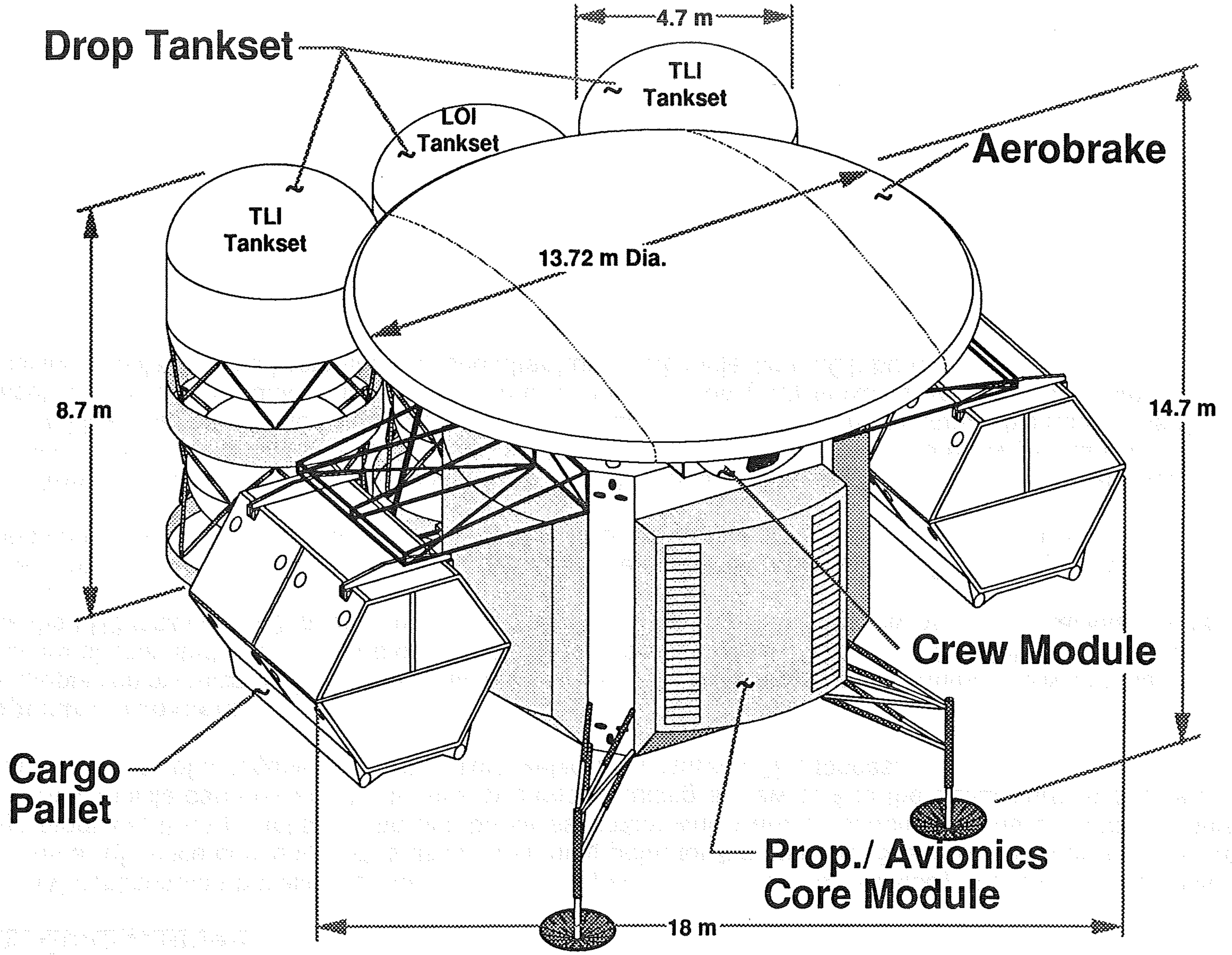
### Propellant Tanksets

The propulsion/avionics core module contains 5 tanks -- 4 LH2 tanks spaced symmetrically around an LO2 tank. The tanks are all mounted to the lower cross beams of the core structure. The LO2 tank is 4.4 m long and 2.9 m in diameter while the LH2 tanks are 4.2 m long and 2.6 m diameter. Total propellant capacity of the core tanksets is 32.5 tonnes

The aerobrake assembly protects the crew during the aeroassisted return to the SSF. The system contains 2 return tank pallets consisting of 3 LH2 tanks and 2 LO2 tanks. Total aerobrake propellant load is 7.2 tonnes.

Each drop tankset consists of 1 LH2 and 1 LO2 tank. The propellant capacity of an individual tankset is approximately 28 tonnes. There are 3 tanksets (2 TLI and 1 LOI) per tank arrangement and there are two tankset arrangements per Lunar vehicle, placed on each side of the LTV. Each tankset has a support structure which connects it to the adjacent tankset as well as the tank vehicle. The Trans Lunar Injection (TLI) tanksets are jettisoned after the TLI burn. The remaining middle drop tanksets are released after Lunar Orbit Injection (LOI) burn.

# Lunar Transfer Vehicle Configuration



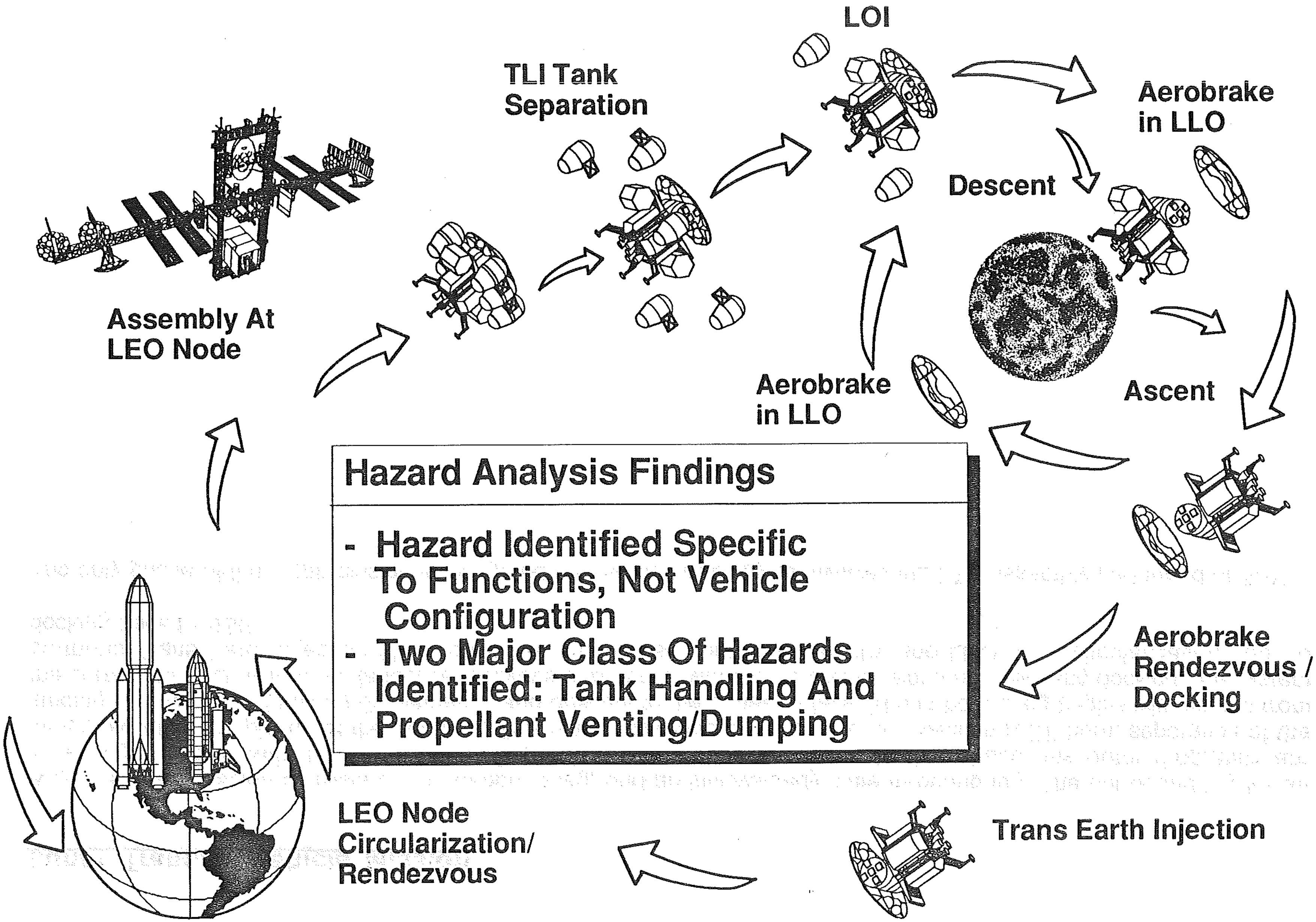

Note: Front Drop Tankset Arrangement Not Shown

## Lunar Transfer Vehicle Mission

A typical lunar mission consists of an out-bound leg, and an initial/steady state in-bound leg. The out-bound leg for an initial flight begins with the Trans Lunar Orbit (TLI) preparation and burn. In this phase, the outer droptanks are separated after completion of the TLI burn. This is then followed by a Lunar Orbit Injection (LOI) burn, separation of the landing & Low Lunar Orbit (LLO) elements, and descent to the Lunar surface. The in-bound leg begins with ascent from the surface to LLO, where the lander rendezvous and docks with the aerobrake element. Following docking, the system performs Trans Earth Injection (TEI), conducts mid-course correction, reentry and LEO node circularization prior to docking back to SSF.

The only phase of the lunar mission investigated for the hazard analysis involves the LTV assembly performed at SSF.

# Lunar Transfer Vehicle Mission




## Hazard Analysis Findings

- Hazard Identified Specific To Functions, Not Vehicle Configuration
- Two Major Class Of Hazards Identified: Tank Handling And Propellant Venting/Dumping

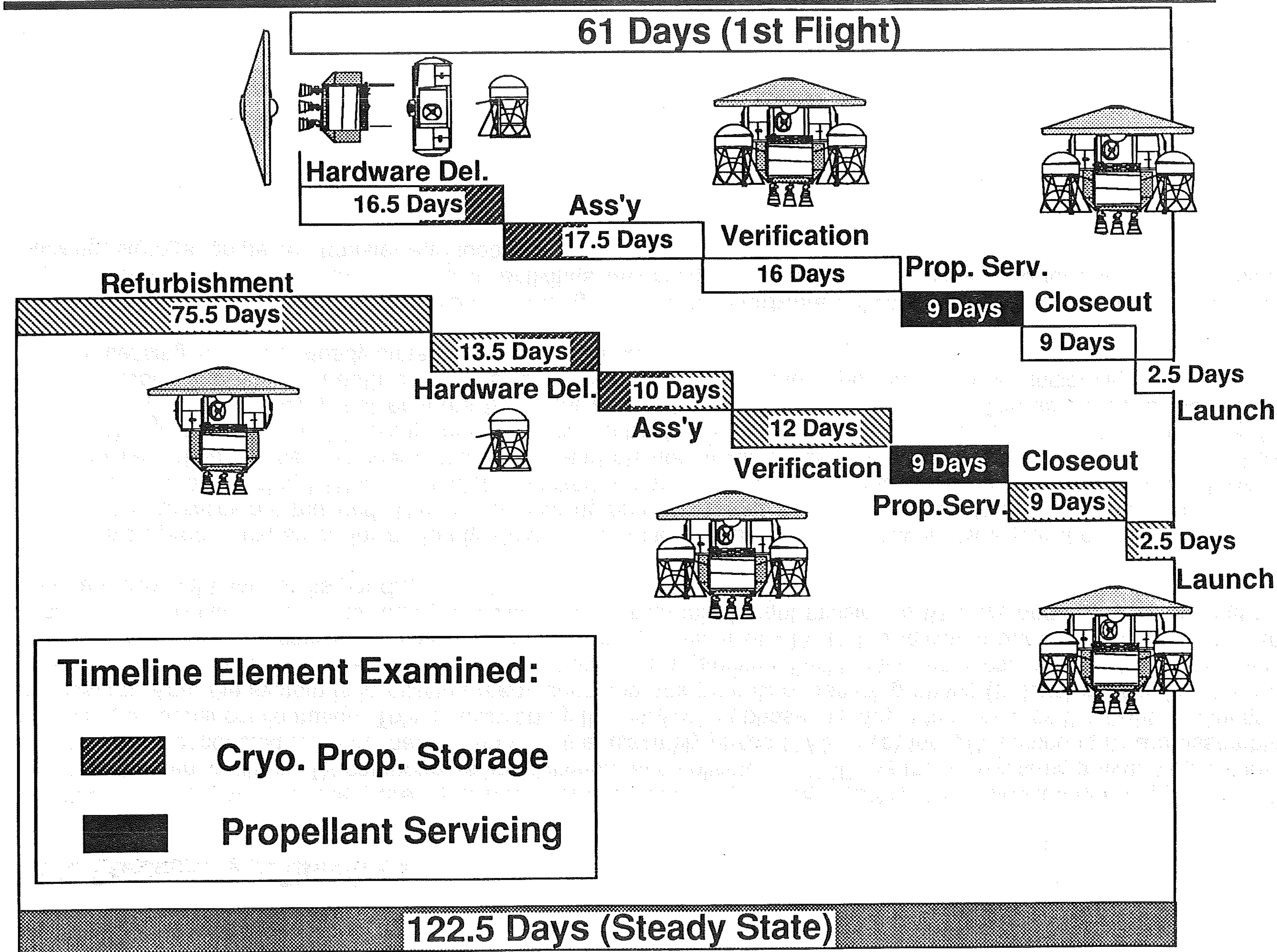
## LEO Processing - Timelines

For the initial flight mission, there are six primary activities performed at LEO (SSF). The hardware delivery phase (16.5 days), is the period when LTV components are delivered and collected at SSF. As the subsystems arrive, element level checkouts are conducted to verify their integrity. In the assembly phase (17.5 days) the LTV components are assembled into an operational configuration. This is followed by the verification phase (16 days) that ensures the flight readiness of the system. After the system is in mission ready condition, the propellant servicing phase (9 days) assembles the drop tanks to the mission vehicle. The closeout phase (9 days days) provides final launch readiness status. The last activity is the launch phase. This consist of mission crew boarding, transfer of LTV to the injection burn area and initiating the Trans Lunar Injection (TLI). The total processing time for an initial flight mission is 61 days and it was assumed that there are two eight hour shifts per day.

The mission processing steps for a steady state mission increased from six to seven. However the times required for many of the activities are reduced. The first processing phase of a steady state mission is the refurbishment phase (75.5 days), where the returning LTV is completely checked out and refurbished. In the hardware delivery phase (13.5 days), the propellant drop tanksets are delivered at SSF and element level checkouts are conducted. In the assembly phase (10 days), the replaceable LTV components are assembled into an operational configuration. This is followed by the verification phase (12 days) that ensures the flight readiness condition of the system. The servicing, closeout, and launch phases are similar in both procedure and processing time to those performed for an initial flight mission. The total processing time for a steady state mission is 122.5 days

The time elements of interest during LEO processing occur in the hardware delivery, assembly,and propellant servicing phases. During portions of these phases, activities involving cryogenic propellants are performed. These include docking, storage, propellant transfer and topoff.

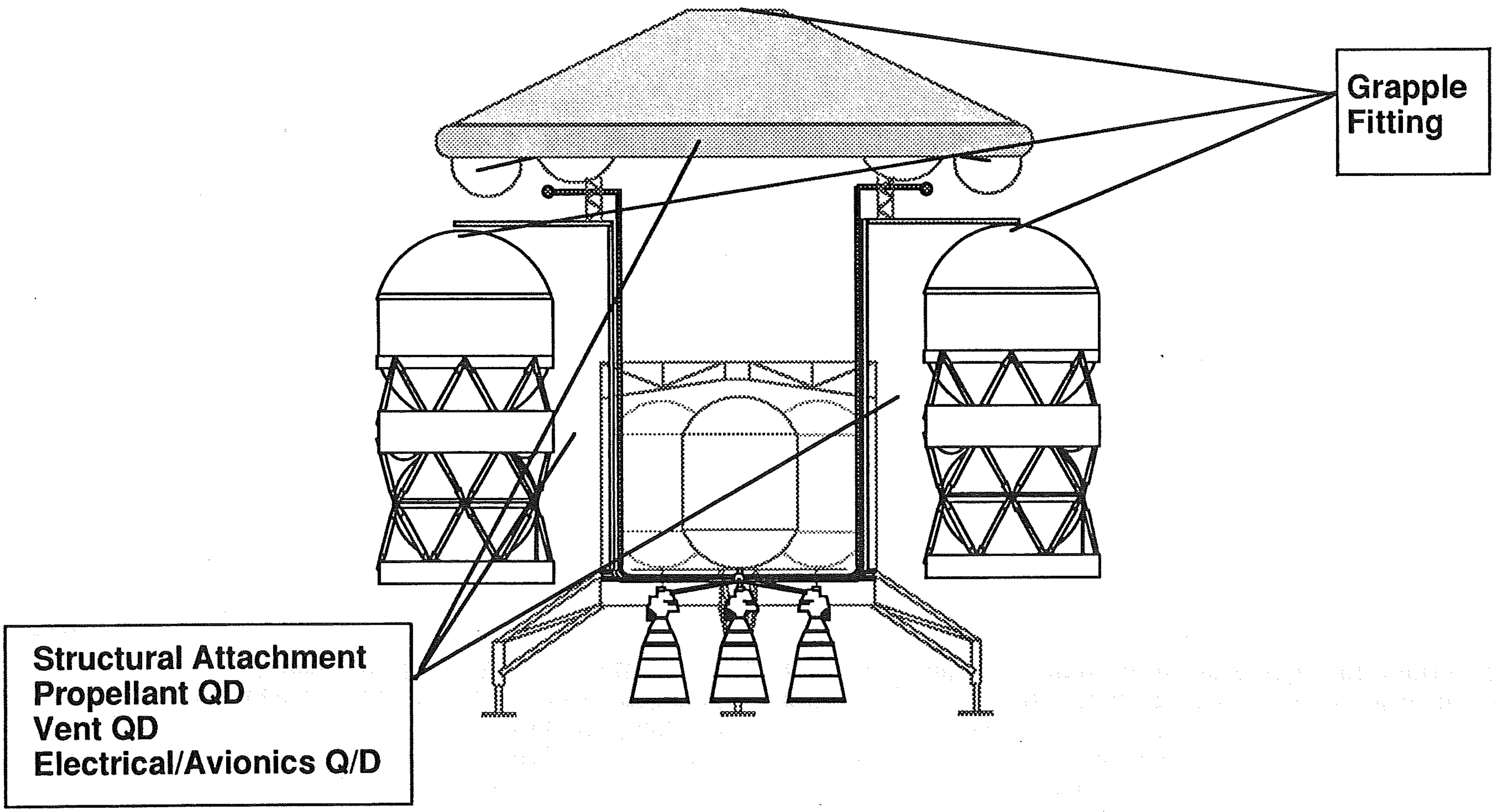
# LEO Processing - Timelines



## LTV - Typical Interfaces

The majority of the hazards identified in the study are failures that originate at the various vehicle/SSF interfaces. These interfaces include structural attachments, propellant line quick disconnect's (QD's), vent QD's, electrical/avionics QD's and grapple fittings used for RMS translation. Failure modes associated with these interfaces are a function of the components involved and are independent of vehicle configuration since these interfaces will be inherent in most vehicle designs. Changes in the LTV configuration would primarily result in differences in the number of interfaces required.

# LTV - Typical Interfaces



## LTV Refueling Activities

Subtask 2 examines cryogenic propellant refueling hazards. The refueling activities performed include drop tank changeout, drop tankset topoff, core tankset propellant loading and aerobrake tankset propellant loading. Droptank changeout consists of translation of the drop tanks using the RMS and attachment to the core LTV. Drop tankset topoff is performed using the mini-depot to replenish boiloff losses of 2%/month. Other refueling activities of concern involve the propellant loading of both the core and the aerobrake tanksets. Propellant for these tanksets is supplied from the drop tanks. Transfer line and tank chilldown are performed prior to the transfer process.

# LTV Refueling Activities

- Drop Tank Change-Out
- Drop Tankset Topoff With Mini-Depot
- Core Tankset Propellant Loading
- Aerobrake Tankset Propellant Loading

## LTV Refueling Functional Summary

This chart lists the major functions performed during the refueling activities. These functions are an inherent part of orbital cryogenic propellant resupply regardless of the tank size, geometry, or vehicle configuration.

# LTV Refueling Functional Summary

- Leak Check/Mate/Demate Of Quick Disconnect
- Propellant Tank/Transfer Line Chilldown
- Tank Propellant Load In Low Gravity Environment
- Tank Venting/Dumping - Nominal And Emergency
- Transfer Line Purging/Safing
- Tank Transport/Handling

**Functions Are Generic - Not Dependent On A Specific Vehicle Configuration**

## Representative Timeline/Hazard Tables

This chart shows a representative illustration of the tables generated during the hazard analysis. Under subtask 2, a total of four timeline operations corresponding to the number of refueling activities were created. The refueling activities have been broken down into detailed steps along with their respective operation times. These times were derived from a ground operations data base and adjusted for LEO operations. The timelines are consistent with previously derived numbers*.

Seven hazard tables were created using the refueling timelines. The hazard tables further break down the refueling operation into detailed steps and identify hazards associated with each. Potential effects on SSF elements are described and severity of impacts are established using the standard NASA hazard categories. These categories range from catastrophic to negligible. All potenital hazards, regardless of their probability of occurrence, were considered.

*Lunar Transfer Vehicle On Orbit Processing Study, Contract NAS10-11400; McDonnell Douglas Space Systems Company; December 1990

# Representative Timeline/ Hazard Tables

## Drop Tankset Propellant Top-off

| Operation | Time (hrs / No. Of Shifts) |
|---|---|
| Prepare Mini-Depot For Propellant Transfer | |
| Mate Transfer Line Umbilicals | |
| Leak Test Conn | |

**Four Timelines Developed For Refueling Operations**

| Operation<br>Drop Tankset Top-off | Hazard | SSF Element Affected | Potential Effect On SSF Element | Crit |
|---|---|---|---|---|
| 1 Close Mini-Depot Vent Iso-Valve And Verify Shut | 1a Iso-Valve Fails To Close<br>1b Unexpected High Propellant Pressure | Crew, Hangar Truss Assy, GN&C | 1a Delay Of Drop Tank Topoff Operations<br>1b Overpressure Can Result | 1a MA |

**Seven Hazard Tables Developed With 39 Operational Steps**

## Refueling Hazard Criticality Summary

The hazards identified in the refueling operation fall under two major categories. The first one involves collision of drop tanks during translation and the second category is the propulsive venting/dumping of propellants. Under the first category, the hazards identified are propellant slosh and remote manipulator system (RMS) failure resulting in loss or degraded control functions. Also included as potential hazards are interface hardware failures such as the grapple connection. The second category, propulsive venting/dumping, occurs from either two-phased venting or uncontrolled venting due to tank rupture.

Summary of identified hazards are shown below for the refueling scenario. The majority of the hazards are categorized as either catastrophic or critical and therefore require mitigating solutions.

# Refueling Hazard Criticality Summary

## Major Hazards Identified:

- Collision During RMS Transport Of Drop Tanks
  - Excessive Slosh, Exceeds RMS Control Capabilities
  - RMS Electr./Mech. Failure (Loss Of Control)
  - Structural Failure Of Interface Hardware
- Propulsive Venting/Dumping Of Propellants
  - Emergency Venting Due To Excessive Pressure Buildup ( Thermal Control Degradation, Vent System Component Failure, Ventline Blockage Due To Frozen Propellants)
    - Two Phase ( Liquid/Gas) Propulsive Venting

## Refueling Hazard Criticality Summary (Cont.)

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# Refueling Hazard Criticality Summary (Cont.)

- Venting Due To Tank Rupture
    - Uncontrolled Venting May Impart Excessive Loads To Truss Element Or Exceed GN&C Capabilities
    - Propellant Impingement On Crew And Equipment

| Preliminary Criticality/Number | |
|---|---|
| • Catastrophic | 29 |
| • Critical | 14 |
| • Marginal | 8 |
| • Negligible | None |

⇨

**Mitigating Solutions Have Been Identified To Eliminate Or Lessen The Severity Of The Majority Of Catastrophic And Critical Hazards**

## Preliminary Hazard Mitigating Solutions

Hazard and safety issues identified will be studied in detail to determine the range of measures which will either eliminate or reduce their probability or impact. These measures include hardware design changes, imposing additional requirements on the LTV and SSF, procedure modification, and redefining the Lunar mission scenario. For those hazards (identified as catastrophic or critical) without effective mitigating solutions, the risk involved with each hazard (determined by the probability of occurrence) will be evaluated. The evaluation of mitigating solutions has been initiated and some sample solutions are summarized in the chart. Many of the hazards can be addressed by incorporating adequate redundancy in key subsystems or components such as multiple vent lines. Other hazards involving those resulting from inadvertent collision can be lessened by incorporating measures to reduce damage to key subsystems such as the thermal protection system

# Preliminary Hazard Mitigating Solutions

- Determine Measures To Either Eliminate Or Reduce The Probability Or Impact Of Identified Hazards Through:
  - Design Changes
  - Additional Requirements
  - Procedure Modifications
  - Different Mission Scenarios

- Sample Preliminary Solutions:
  - Increased Component Redundancy In SSF And LTV Subsystems
  - Multiple Vent Lines
  - Robust Thermal Protection System On Propellant Tank For Lower Susceptability To Damage

## Preliminary Hazard Mitigating Solutions (Cont.)

There are ongoing or planned technical development efforts related to cryogenic fluid management that will demonstrate or validate technologies and processes to support solutions to the identified hazards. These include the ground test programs at NASA Lewis Research Center and Marshall Space Flight Center. These ground test activities are demonstrating techniques for low gravity cryogen transfer, active and passive tank pressure control, thermal insulation concepts, and advanced instrumentation. Flight experiments are underway or planned which would provide low-g validation of the ground test results.

# Preliminary Hazard Mitigating Solutions (Cont.)

- Technical Development Effort Related To Cryogenic Propellants Are Ongoing Or Planned Which Will Demonstrate/Validate Mitigating Solutions
  - Cryogenic Ground Test Programs At NASA Lewis Research Center And Marshall Space Flight Center
    - Cryogenic Storage/Transfer/Pressure Control
  - Fluid Flight Experiments
    - Low-g Validation Of Ground Tests

## Future Activity

Subtask 3 and 4 will complete the cryogenic propellant hazard analysis. Subtask 3, identification of hazards, risks and safety issues associated with vehicle operation other than refueling, have just been recently completed. Subtask 4, identification of mitigating measures to eliminate or reduce risk, will be completed by 9 August 1991.

# Future Activity

- Subtask 3 - Vehicle Operations Risk/Hazards Evaluation
  - Drop Tankset Docking/Storage
  - Turnaround Operations, Vehicle Safing
  - Orbital Debris/ Micrometeoroid Effects
  - Long Term Thermal Control Degradation
- Subtask 4 - Identification Of Mitigating Solutions
  - Determine Measures To Reduce Or Eliminate Risk/Hazard Identified In Subtask 2 And 3
    - Mission Scenario Changes, Operations And/Or Design Solutions

INFORMATION SCIENCES DIVISION
AEROSPACE SYSTEMS DIRECTORATE

## Space Station Freedom Program
## Data Management Systems

# Beyond the Baseline

# The Space Station Evolution Symposium

## Data Management System Advanced Architectures


Ed Chevers JSC / ARC


NASA
Ames Research Center

# Data Management System Concept

- The Data Management System is unique in the Space Station
  - It has no "function" like other subsystems, i.e., it does not generate a state vector, or maintain cabin temperature, or hold vehicle attitude, etc.
- The Data Management System provides a set of services for all other subsystems
  - Provides computational resources
  - Transmits commands, messages and data between application programs
  - It is the means by which avionic systems integration is accomplished
- Since every subsystem is dependent on the DMS, it was identified as a long lead item during Phase B studies ..... not because it was technically difficult, but because it had to be ready before any other subsystem design could be finalized
- Any other Space Station subsystem can be modified, enhanced or replaced with new technology and only has to reverify a single interface with the DMS
- Before the DMS data bus network, processor, operating system or system software can be changed in any way, potential impacts to every subsystem must be determined

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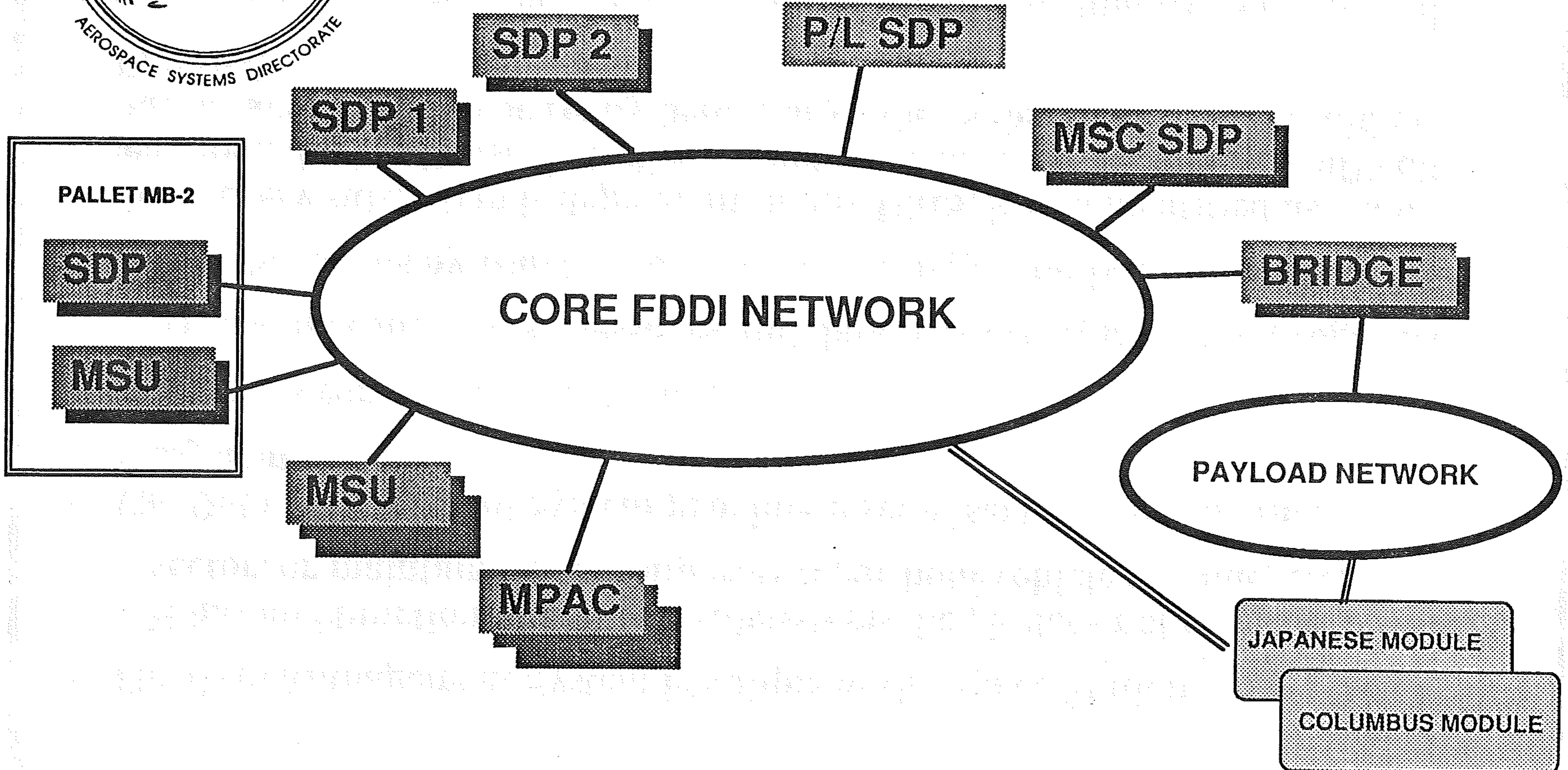
# Data Management System Simplified Schematic

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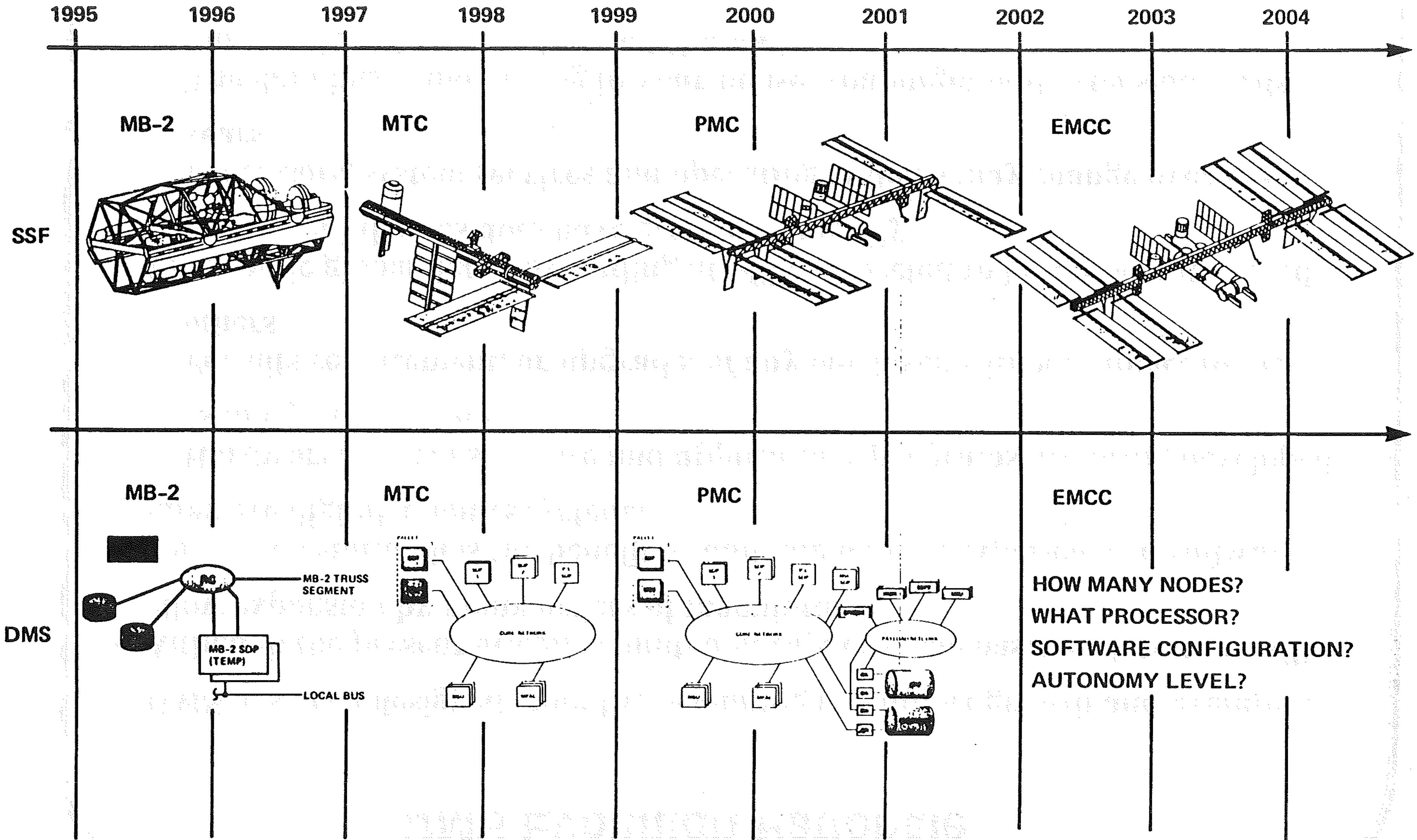
# DMS Evolution Rationale

- DMS has been designed from the beginning to support growth and evolution
- Although the present design is limited in capacity, the basic architecture will allow expansion by many orders of magnitude
- The Space Station has the benefit of building on past experience in software intensive digital avionics systems
  - Hardware, system software and applications programs are being developed as independent layers
  - Permits replacement, or upgrade, of any one layer without impact to the others
- Fiber optic global data bus loading at MTC expected to be < 5% of its stated capacity, and the bus does have growth capability
  - Processors, system services and operating systems may change over the years
  - The data bus is like wiring in your house, you might add extension cords but you do not want to tear out the walls

# DMS EVOLUTION LINKED TO STATION CONFIGURATION
## "FOLLOW-ON-PHASE"

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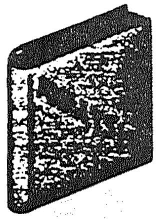
# The DMS Advanced Architecture Task

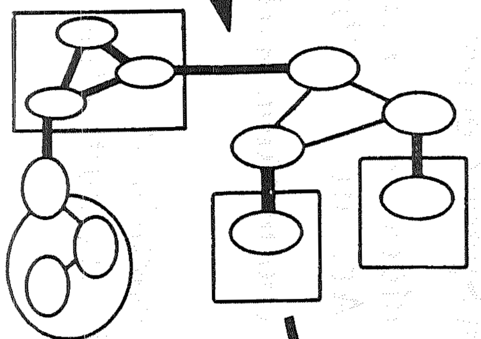
- The time to consider evolution is during the original design phase
- Although hard lines must be drawn and the final flight designs developed, growth and evolution paths can be defined based on technology projections
- The DMS Advanced Architectures task at the Ames Research Center has been chartered by the Level 1 Space Station Engineering Office to evaluate potential candidates for DMS growth and evolution
  - Task includes: hardware and software technology, system software enhancement, payload augmentation and software tool evolution
  - Task is done in coordination with Johnson Space Center
  - Status reports presented to other Nasa Centers and contractors at quarterly SATWG meetings and monthly Architecture Panel telecons
  - Payload integration studies being done in cooperation with several Ames payload research scientists
- An advanced development test bed is being assembled to support simulations and analytical studies with hardware and software evaluation

# DMS TASK APPROACH
## INCREASING LEVELS OF FIDELITY



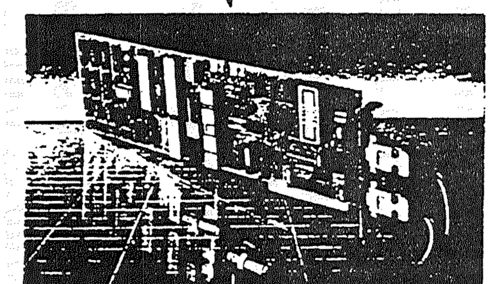
Analysis/System Engineering

- Document Review
- Design Review Attendence
- User Requirements
  - Payloads
  - Subsystem
  - Operations
  - Crew



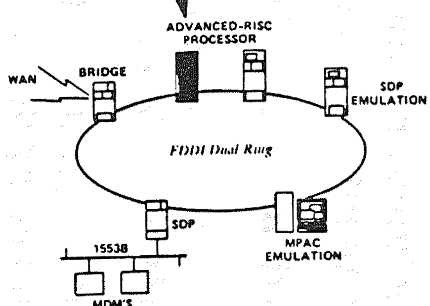
Simulation & Benchmarking

- Network Simulation
- Processor Performance Prediction



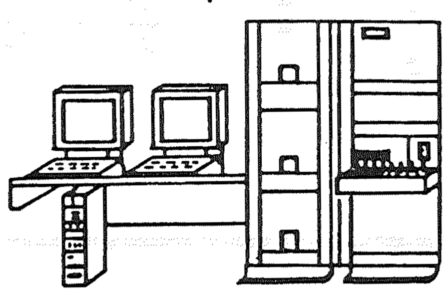
Isolated Hardware Testbeds

- 1553 Local Bus
- FDDI
- 386/486 Platforms




Integrated Hardware Testbeds

- System Level Performance Issues
- Software Engineering



DMS Kit

- Track SSF Design
- Software Development

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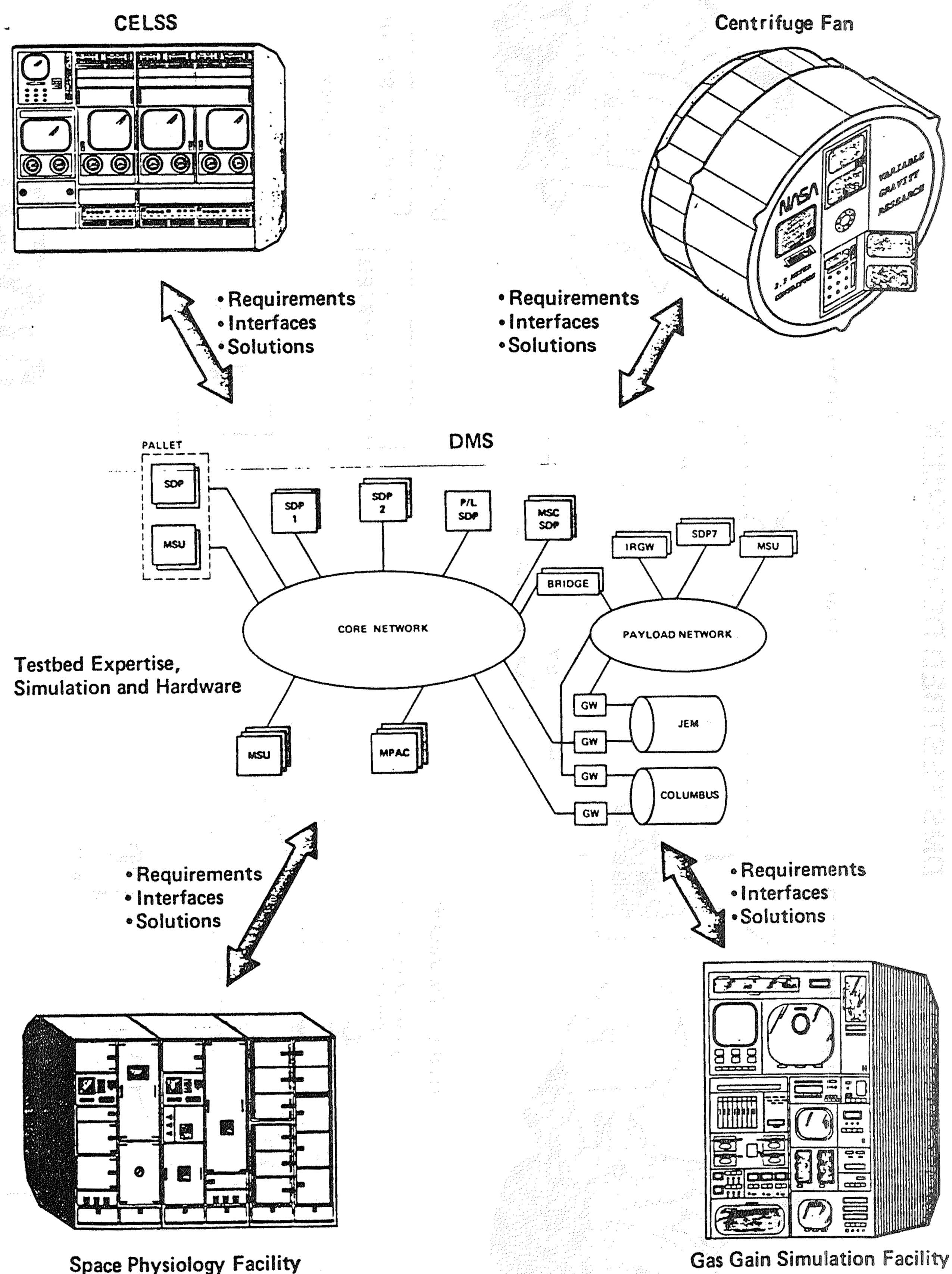
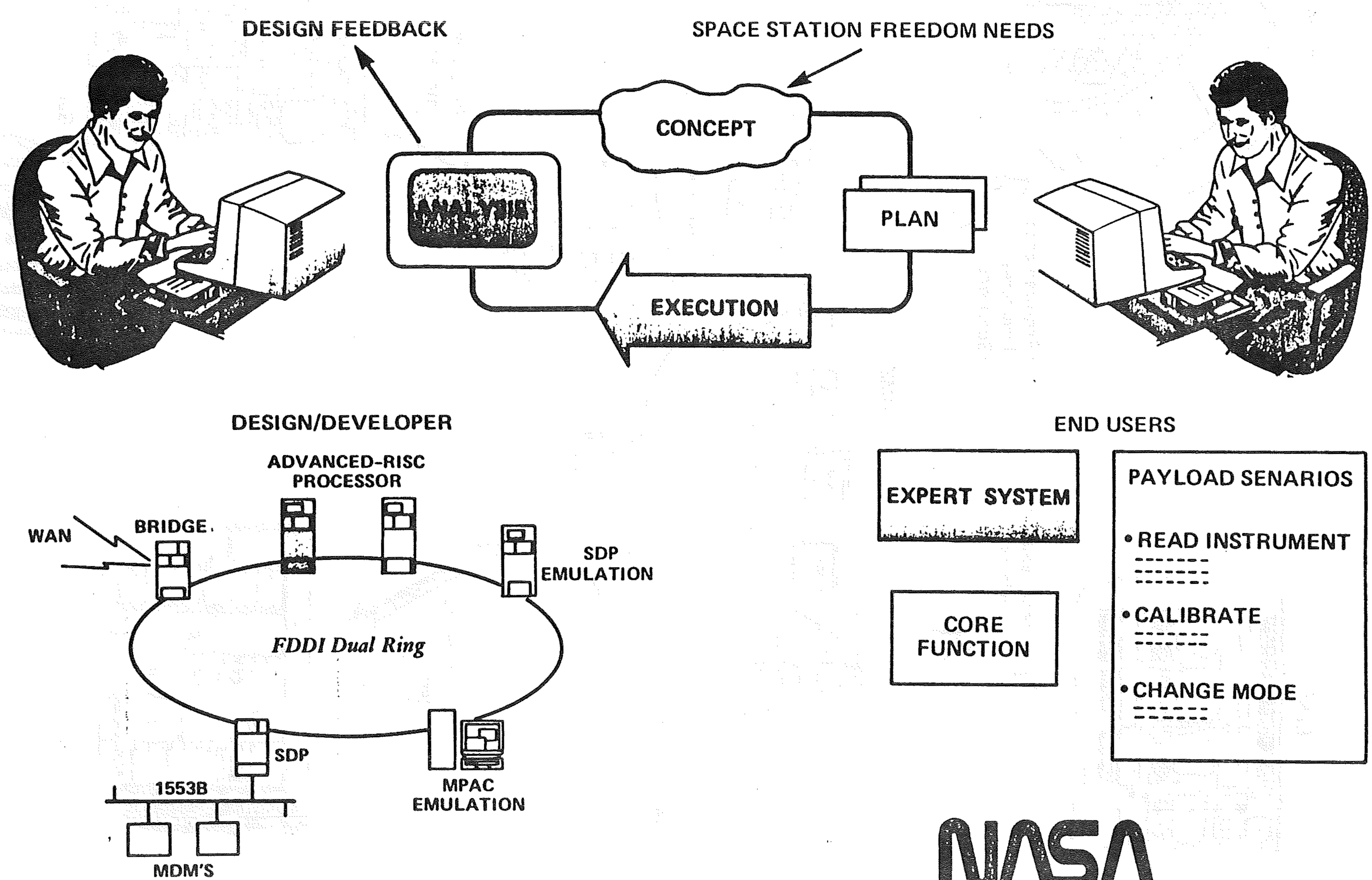
# DMS GROUP SUPPORT FOR AMES PAYLOADS



# DMS TESTBED DEVELOPMENT

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# The DMS Advanced Architecture Task Status

- Detailed evaluation of 386 processor selected for the Station EDP completed
  - Determined that flight processor will have 3 MIPS computational speed compared to 4 MIPS for commercial equivalent
  - Difference is due to absence of cache memory in flight unit
- Recommended that Station Project Office not consider the 486 as a viable upgrade candidate
  - 486 has on-chip cache memory but it does not have parity
  - Flight units are susceptible to single event upsets (SEU) from high particle impacts and high density memory chips need parity or EDAC
- Have arranged for early delivery of 586 chips from Intel for evaluation
- Commercial version of FDDI has been received and evaluation tests started
- Three advanced parallel processing systems developed by DARPA are being evaluated for increased computational capacity and fault tolerance
- Technique for converting digraph models to fault trees for reliability analysis has been completed. Fault tree to digraph conversion now under consideration

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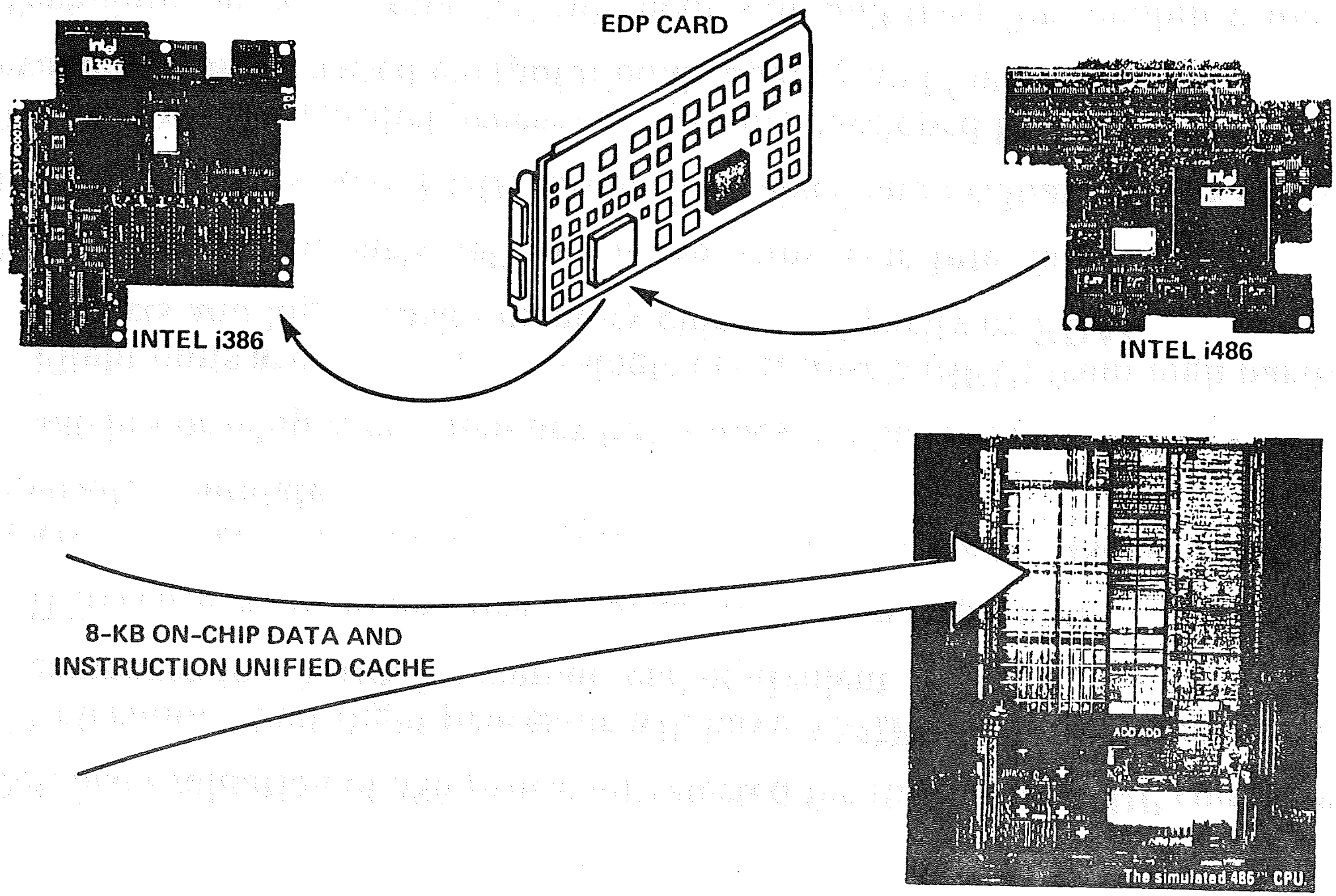
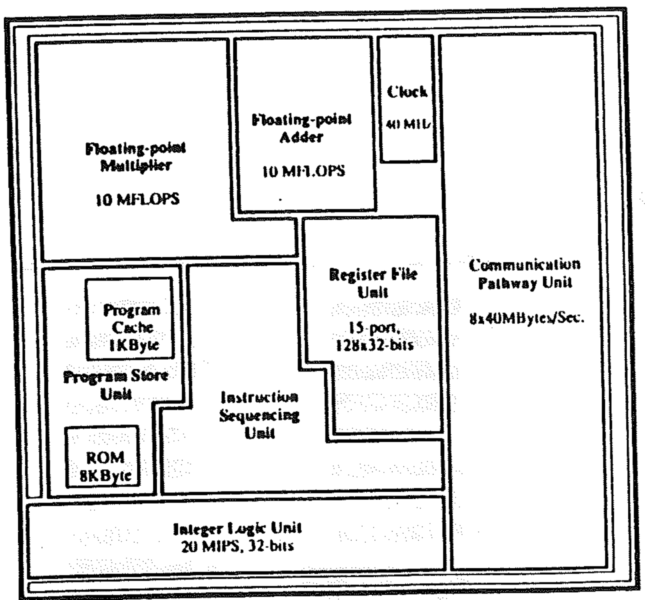
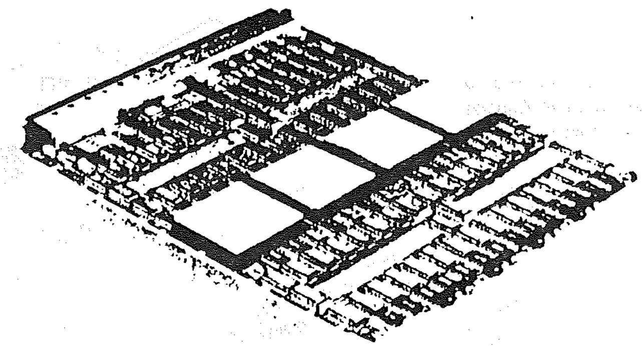
# ANALYSIS OF THE INTEL 386 AND i486 MICROPROCESSORS

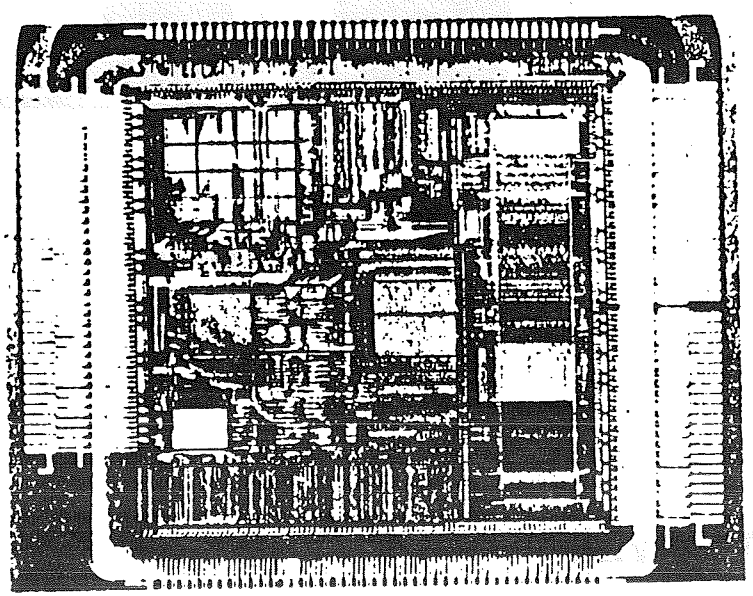


# DARPA iWARP PROCESSOR EVALUATION

iWarp Functional Unit Placement





Task to evaluate a DARPA-sponsored processor and software architecture for future Space Station Freedom DMS upgrades through applications testing.

- Evaluation of iWarp integration into DMS baseline architecture.
- Seven degree-of-freedom spatial motion planning application on the iWarp.
- Complex sensor processing applications on the iWarp.

The goal of this work is to determine the iWarp's suitability as a processing device for space missions.

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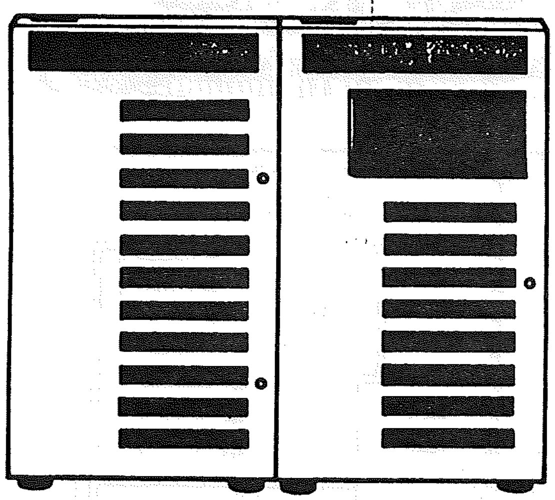
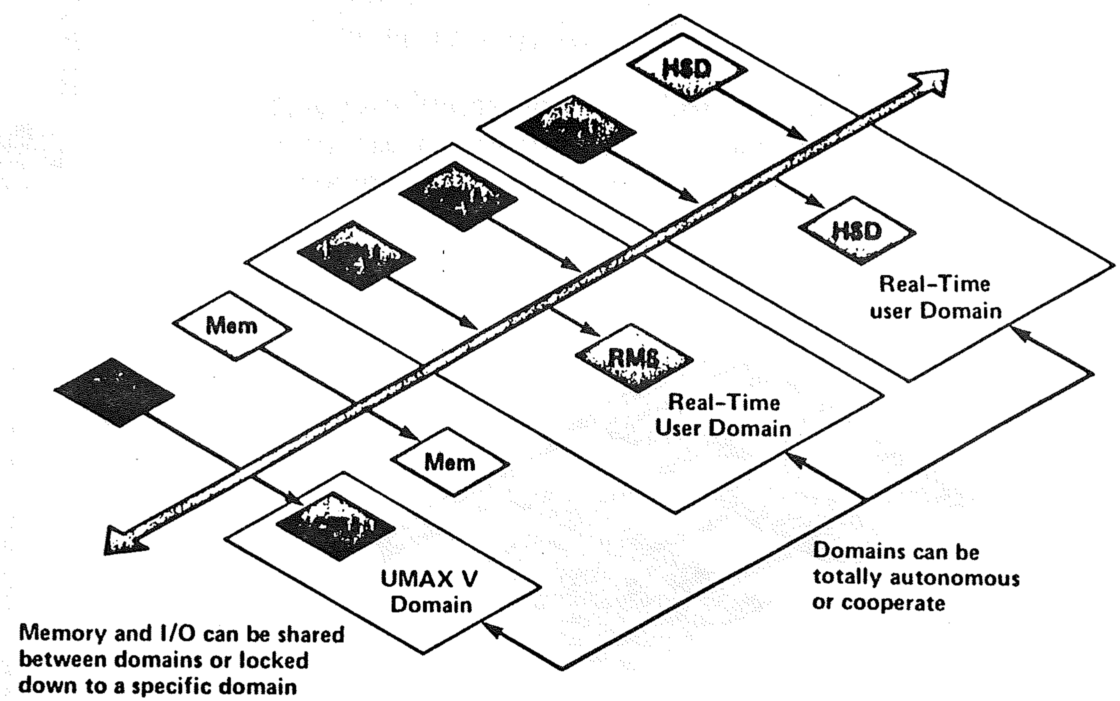
# SOFTWARE ENGINEERING

# REAL-TIME-MULTI-PROCESSOR TESTBED

**ENCORE MULTIMAX**



**ARCHITECTURE OVER VIEW**

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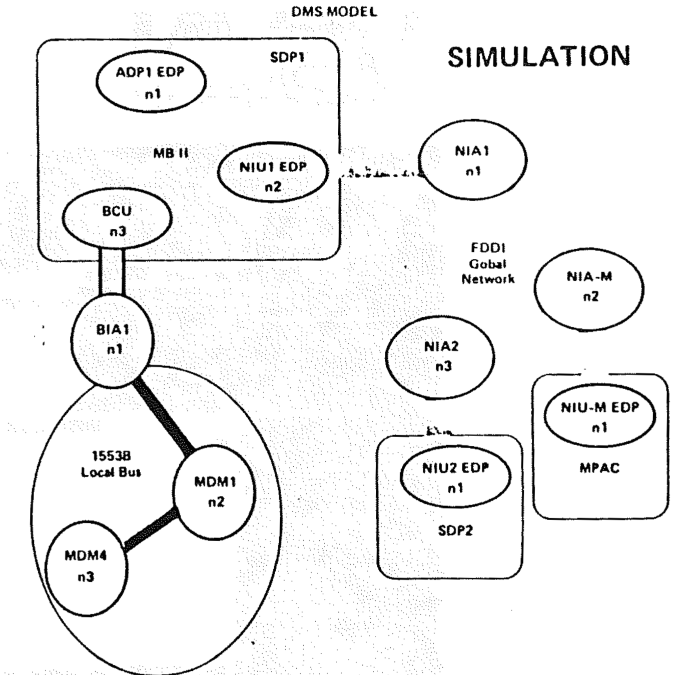
# NETWORKED PROCESSOR PERFORMANCE

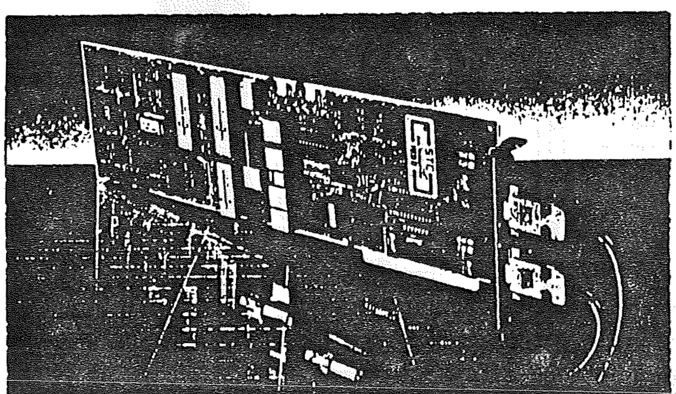
## DESIGN ISSUE

- SYNCHRONIZATION
- FUNCTION LATENCY
- PERFORMANCE BOTTLENECK
- EXTENDED REQUIREMENTS

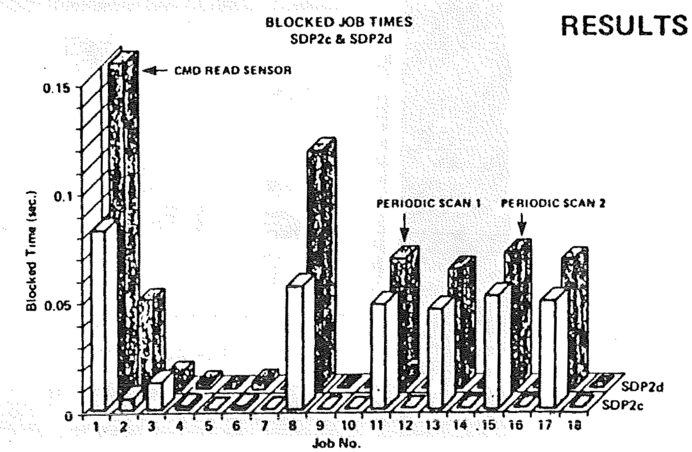
SIMULATION




EMULATION



RESULTS

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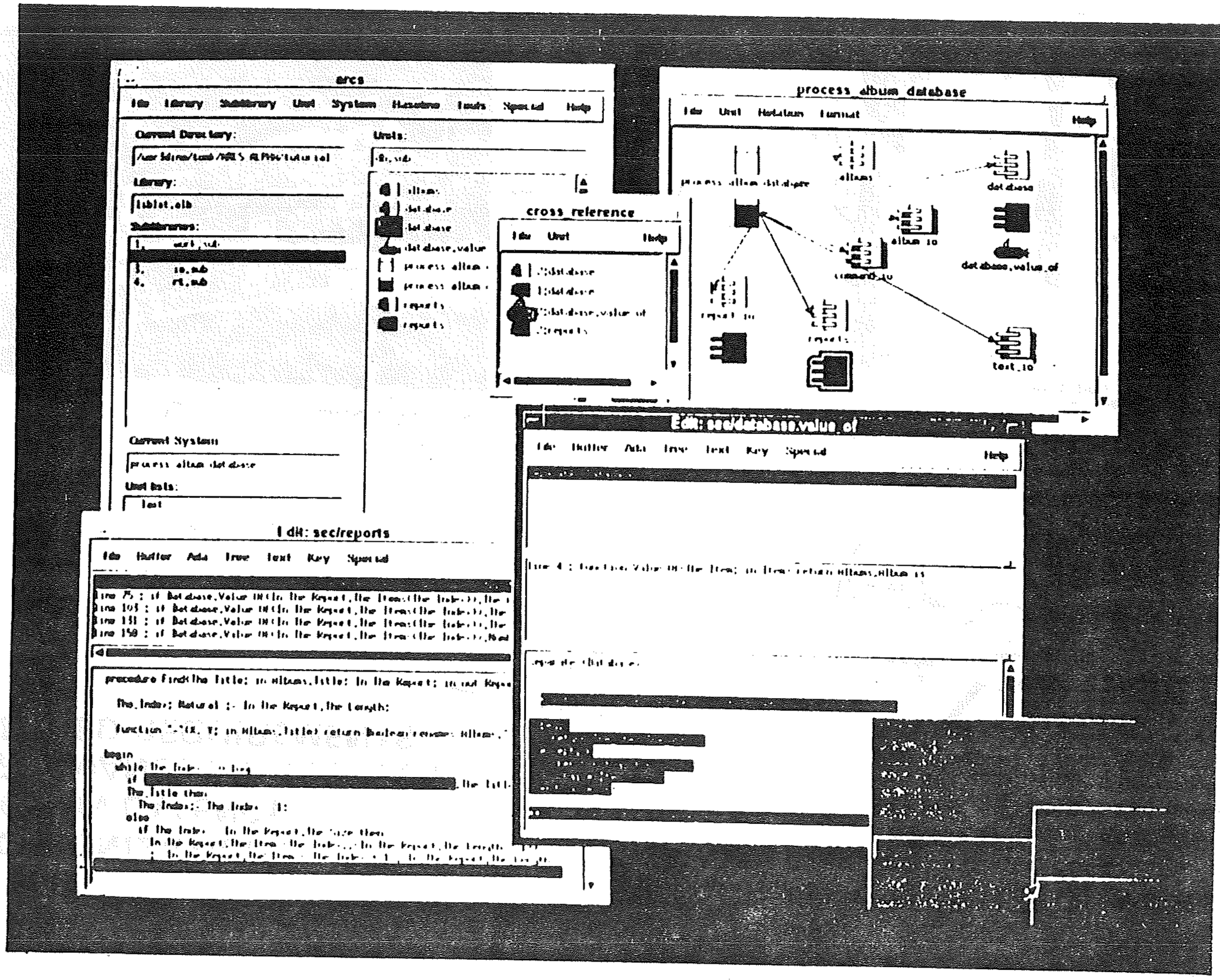
# ADVANCED SOFTWARE ENGINEERING TOOLS

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# DMS Advanced Architecture Task 92 Goals

- Begin timing studies of the Station Lynx OS with Ada application programs
- Start colaborative effort with UC-Davis on detailed evaluation of the Space Station Ada compiler
- Initiate long term effort on techniques for dynamically updating DMS operating system
- Continue evaluation of parallel processers and expand fault tolerant system investigations
- Begin detailed testing of 586 processor
- Prototype an end-to-end payload experiment to define DMS capabilities and limitations
- Develop a detailed Ada model of the on-board RODB for use in cooperative Ames/JSC/UH-CL flight data base testing
- Implement a multi-node test bed that emulates the flight configuration plus additional nodes for a payload command station, ground control console and advanced fault tolerant processors for growth potential

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# OPTICAL PROTOCOLS FOR ADVANCED SPACECRAFT NETWORKS

*Presented at NASA Space Station Evolution Conference, Houston, TX*

**Dr. Larry A. Bergman**

JPL

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August 7, 1991

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# OVERVIEW

Most present day fiber optic networks are in fact extensions of copper wire networks. As a result, their speed is still limited by electronics even though optics is capable of running three orders of magnitude faster. Also, the fact that photons do not interact with one another (as electrons do) provide optical communinication systems with some unique properties or new functionality that is not readily taken advantage of with conventional approaches. This paper describes some of the motivation for implementing network protocols in the optical domain, a few possible approaches including optical CDMA, and finally how this class of networks can extend the technology life cycle of the space station with increased performance and functionality.

# OVERVIEW

- Why optical?
- NASA needs
- Network bottleneck areas
- Possible solutions
  - components
  - architectures
- Spectral CDMA
- Technology availability

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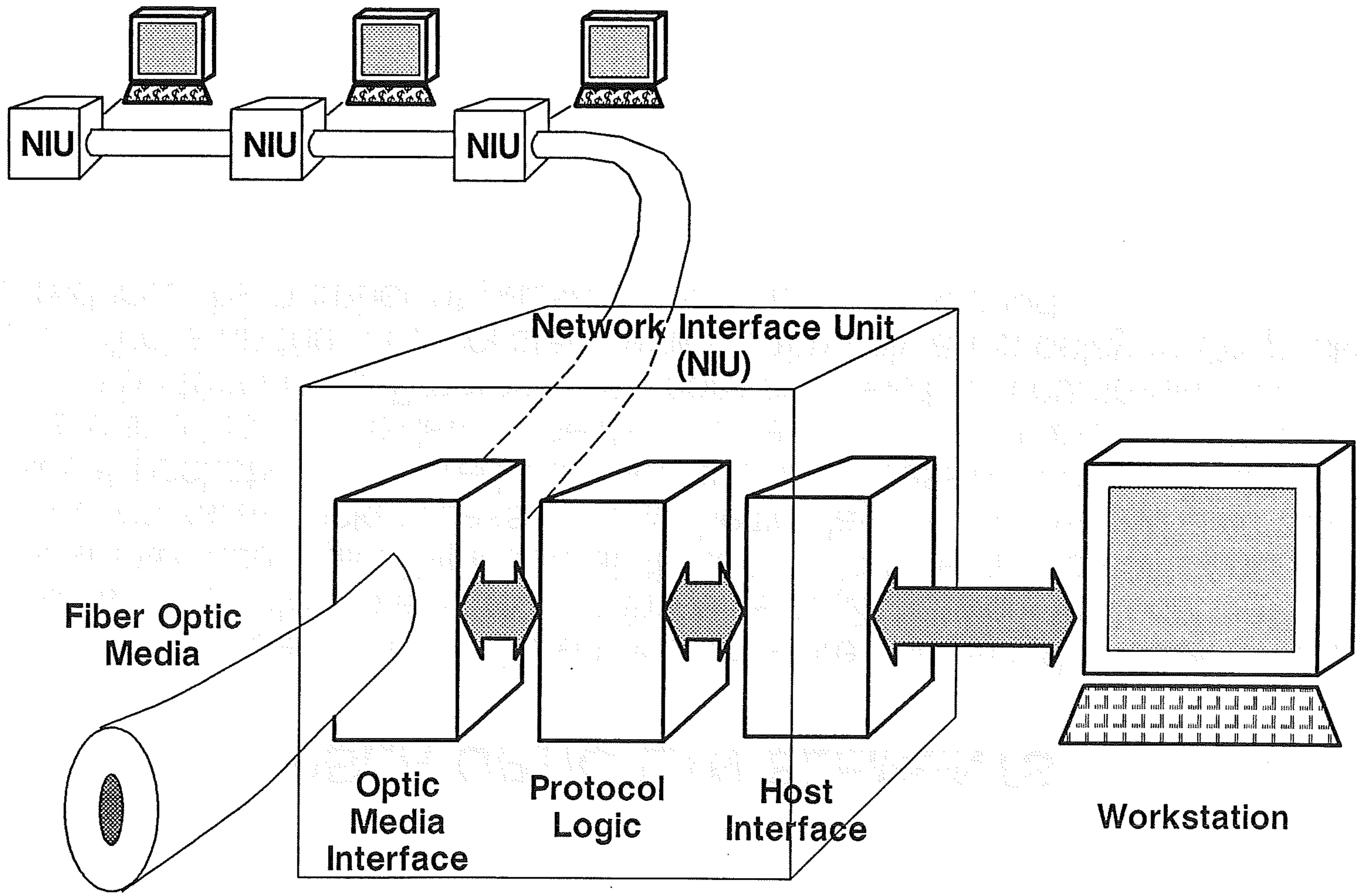
# FIBER OPTIC LAN ELEMENTS

Contemporary fiber optic local area networks are comprised of three principal elements: (1) photon to electronic transceivers, (2) network protocol logic, and (3) host interface logic. Typically, all three employ electronic components. In most networks, all packets pass through the first layer to the second layer where non-local packets are filtered out. Additional processing occurs in the host interface and the host to determine the nature of the packet and to what service it should be forwarded. Progressively more overhead is accummulated as the packet climbs up the protocol stack which ultimately adds delay to the packet and reduces the number of packets transmitted by second.

# FIBER OPTIC LAN ELEMENTS



# BACKGROUND

By implementing the network protocols in the optical domain, the electronic bottleneck may be circumvented for many of the elementary functions (such as addressing) thereby increasing the packets that can be passed through a node up to and beyond 100Gbit/s. Other advantages include lower power consumption, non-blocking crossbar functionality, and higher security. To realize a fully photonic network, one must be able to implement boolean functions in the optical domain. A method based on spectral code division multiple access (CDMA) permits this style of implementation based on established optical processing techniques. Furthermore, it fully exploits the strengthes of optoelectronic components, and can utilize the full terahertz capacity of optical fibers.

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# BACKGROUND

- All optical local area network technology that provides:
  - very high aggregate speed (>100Gbit/s)
  - crossbar functionality (non-blocking)
  - high security
  - low power

  needed by next generation spacecraft instruments in early '00 (e.g., concurrent processors, optical telecom, etc)

- Optical protocol technology is based boolean functions implemented with coherent fiber optics and spatial spread spectrum techniques

- Exploits THz bandwidth capacity of single-mode optical fibers and non-linear behavior of optoelectronic devices

- Circumvents usual electronic and TDMA throughput bottlenecks

# MOTIVATION

Many different types of applications are on the horizon that will demand higher speed networks including RISC-based instruments, high-rate IR/radar imagers, advanced parallel computers, and possibly optical telecom.

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# MOTIVATION

- Technology supports spacestation, future Earth orbiting satellites, and deep–space probes with high–bandwidth telemetry requirements, such as:
  - synthetic aperture radar (SAR)
  - optical processors
  - spaceborne supercomputers
  - optical memories
  - systolic array signal processors
- *Telescience* – future emphasis in preprocessing data during acquisition to reduce telemetry downlink bandwidth requirements
- Decentralization of resources, data bases, and computational power on a local and national level commensurate with GFlop/TFlop CPUs
- Spacecraft networks with reduced cable weight, low power, and increased security
- Provides communication fabric for HPCI and TouchStone TeraFlop massively parallel concurrent machines

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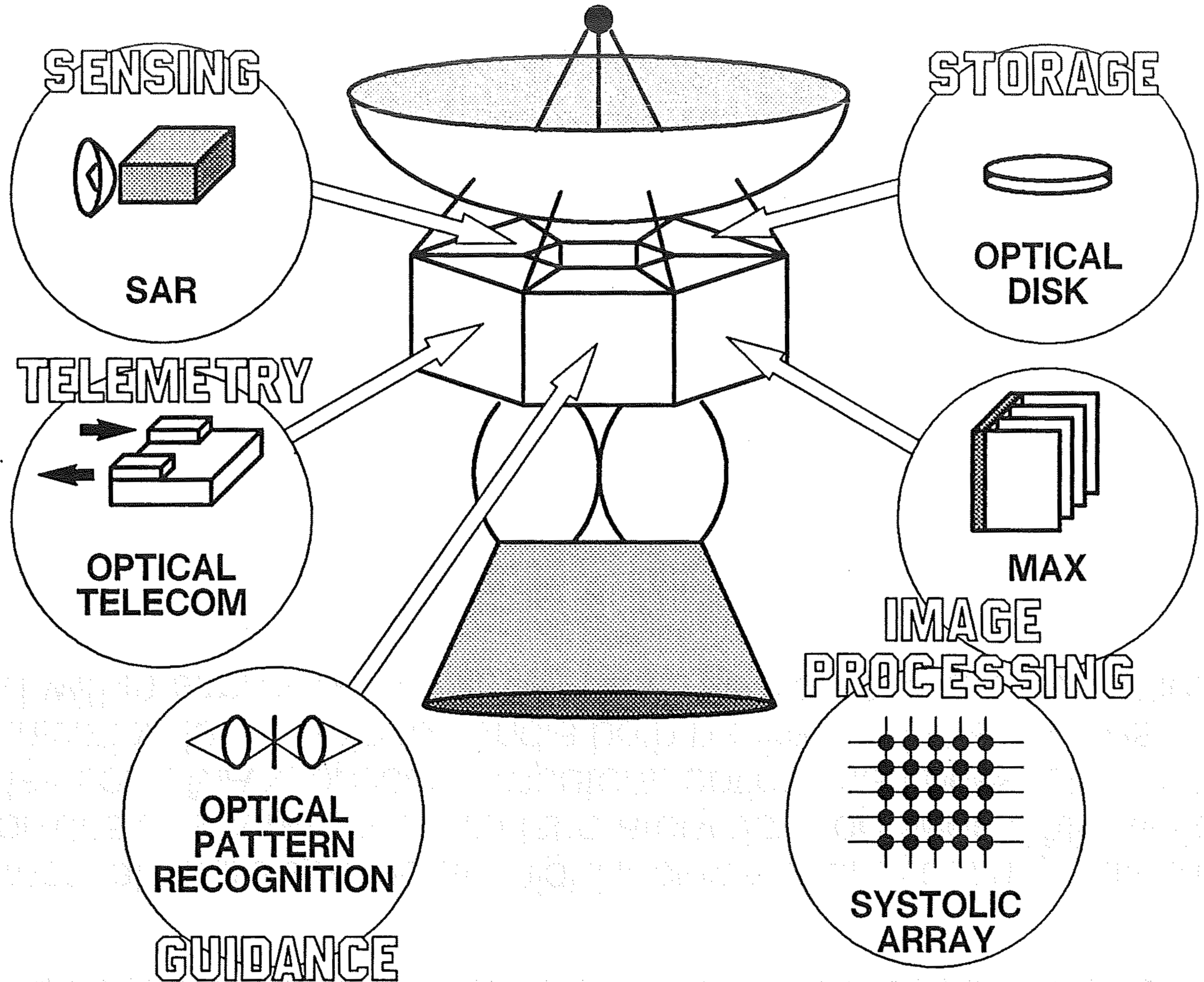
# HIGH DATA RATE SYSTEMS IN FUTURE SPACECRAFT

A hypothetical future spacecraft might include a varieyt of high rate instruments based on designs currently under laboratory development (SAR, systolic arrays, optical telecom, MAX, optical computers, optical memories, etc). A high speed communication fabric able to handle both packet and stream messages will be required within similar power envelopes that we have available today.

# HIGH DATA RATE SYSTEMS IN FUTURE SPACECRAFT




- APPLICATIONS WILL REQUIRE A HIGH-SPEED (0.1-1 GBIT/S) DATA NETWORK ON-BOARD SPACECRAFT FOR BOTH STREAM AND PACKET TRAFFIC

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# EVOLUTION OF UNMANNED SPACECRAFT DATA BUSES

The evolution of unmanned spacecraft data buses at JPL has spanned simple centralized communications topologies through parallel buses to (more recently) high speed networks. A system requirement has always been that the network offer deterministic packet transmission (bounded latency). As speeds and functionality increase, more instruments can be added with an increasingly larger range of services.

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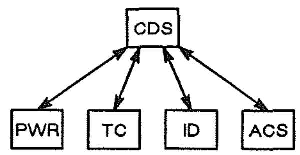
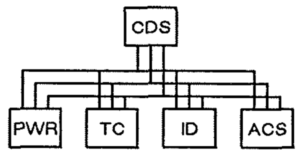
# EVOLUTION OF UNMANNED SPACECRAFT DATA BUSES

## SERIAL & CENTRALIZED



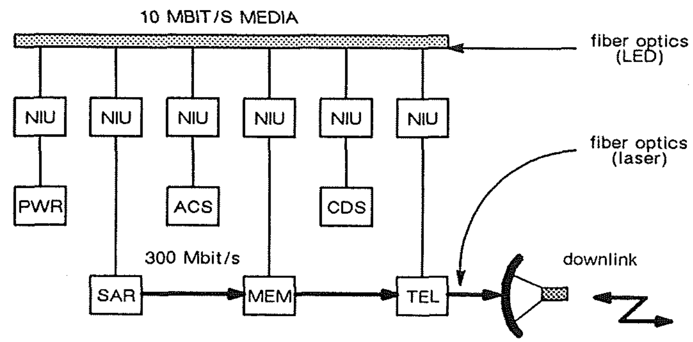

VIKING & VOYAGER
(1970–75)

## PARALLEL BUS



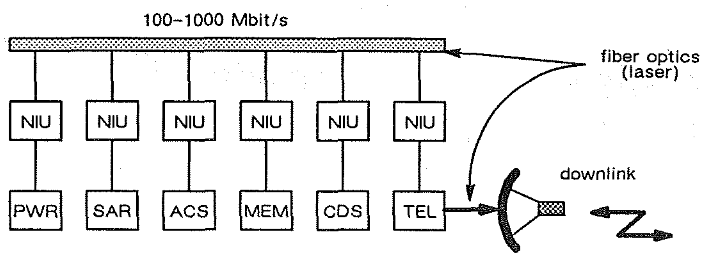

GALILEO
(1975–80)

## LOW SPEED LAN



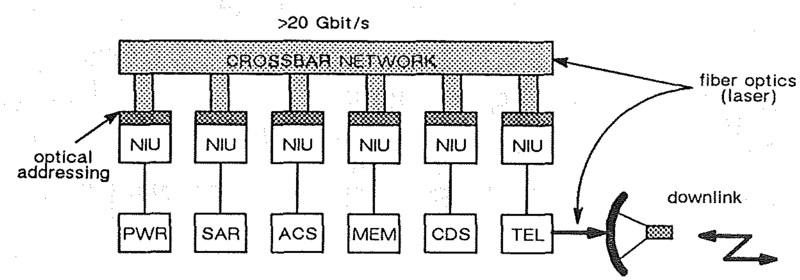

EOS 1
(1990–95)

## HIGH SPEED LAN




EOS 2

## ALL OPTIC LAN




MARS SAMPLE RETURN

*Modular high–speed instruments, such as SAR, HIRIS, optical memories, systolic array and concurrent processors, will require distributed networks with multi–gigabit/sec speeds. An all–optic LAN would ideally overcome the NIU speed limit and provide connection style interfaces to real–time systems.*

# VIABILITY OF FDDI FOR SPACECRAFT

The 100 Mbit/s Fiber Distributed Data Interface (FDDI) has been under development by NASA, DoD, and many commercial companies. Based on a fiber optic dual token ring, the network offers standard multi-vendor interfaces, low EMI/RFI, multi-fault tolerance, deterministic packet transmission. Currently, the NIU logic is available in a small 3-IC chip set.

# VIABILITY OF FDDI FOR SPACECRAFT

## Advantages

| | |
|---|---|
| • Speed matches next generation instrument technology | *SAR, IR Imagers, signal processors* |
| • Fiber optic ready | *all fiber attributes* |
| • Multi-fault tolerant | *enhanced survivability* |
| • Deterministic | *vital for stream traffic, control, heartbeat functions* |

## Disadvantages

| | |
|---|---|
| • High power consumption | *may limit to Earth orbiters* |

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# OBJECTIVE

The main objective of the this research effort is to leapfrog current electronic–based network technology with an all-optic one that provides 100X improvement in speed, non-blocking crossbar functionality, and hybrid services (packet and stream). It also intends to demonstrate optical protocols with an existing space station DMS testbed, and identify technology availability.

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# OBJECTIVE

- Leapfrog conventional electronics–bound network technology with optics to achieve 100X improvement in capacity, reduced power, and integrated service functionality
- Demonstrate that electronic protocols can be implemented in the optical domain
- Develop DMS network migration paths

# BENEFITS OF LANs IN SPACECRAFT

Networks offer increased speed, simpler wiring, and interchangeable modularity. All these factors enhance making the system easily reconfigurable—and even serviceable—in space.

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# BENEFITS OF LANs IN SPACECRAFT

| | *Impact* |
|---|---|
| • High–speed | *greater throughput* |
| • Daisy chain wiring | *less required cable* |
| • Time Division Multiple Access (TDMA) | *shared user cost* |
| • Standard protocol and interface | *modular instruments, increased testability, off–the–shelf GSE* |
| • Reconfigurable | *changes easily accommodated* |

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# BENEFITS OF FIBER OPTCS IN SPACECRAFT

In addition to enormous bandwidth, fiber optics also provide enhancements in EMI/RFI immunity, ground loop isolation, no external emissions, and small size, weight and power consumption.

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# BENEFITS OF FIBER OPTICs IN SPACECRAFT

| | *Impact* |
|---|---|
| • Light weight | • *greater payload* |
| • Small size | • *smaller right–a–way* |
| • Low power | • *smaller pwr plant* |
| • No emissions (E/M) | • *relaxed routing,*<br>• *boom instruments* |
| • Immune to RFI, EMI, ground loops | • *relaxed routing,*<br>• *simplified integration* |
| • Very large bandwidth | • *supports future*<br>• *instruments* |

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# APPROACH

- Analyze present DMS baseline to establish network topology, protocol, and interface requirements
- Develop and demonstrate two-node optical testbed for stream and packet traffic
- Analyze optical protocol suite tradeoffs and compare with other approaches
- Identify DMS network upgrade paths
- Conduct interface demonstration with another DMS system

# ELECTRONIC NETWORK BOTTLENECK AREAS

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# COMPONENT TECHNOLOGY LIMITS

The speed of state-of-the-art electronics and optoelectronic components currently is about 20GHz while fiber optic media provides three orders of magnitude more capacity (to 50THz). Tapping into this enormous bandwidth is simplified if the electron–based devices can be removed from the first few tiers of the network protocol stack.

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# COMPONENT TECHNOLOGY LIMITS

| | Now | Future |
|---|---|---|
| **Electronics** | | |
| • MESFETs (GaAs) | 15 Gb/s | 35 GHz |
| • HEMT (GaAs @ 77°K) | | 100 GHz |
| • VLSI (GaAs/2K gates) | 5 GHz | 20GHz |
| • VLSI (Si/1K gates) | ~1GHz | 12GHz |
| **Optoelectronics** | | |
| • laser diodes sources (InGaAs/P) | 16 Gb/s | 45 GHz |
| • modulators (LiNb, MQW InGaAs) | 20 GHz | >100 GHz |
| • photodetectors (InP/GaInAs, GaAs) | 20–40 GHz | 100 GHz |
| **Media (L=1Km)** | | |
| coax | 300 MHz | |
| multi–mode fiber | 3 GHz | |
| single–mode fiber | >200 GHz | >10THz |
| **Peripherals** | | |
| processors (RISC) | 25MHz | >200MHz |
| memories (GaAs) | ~1 GHz | >10GHz |

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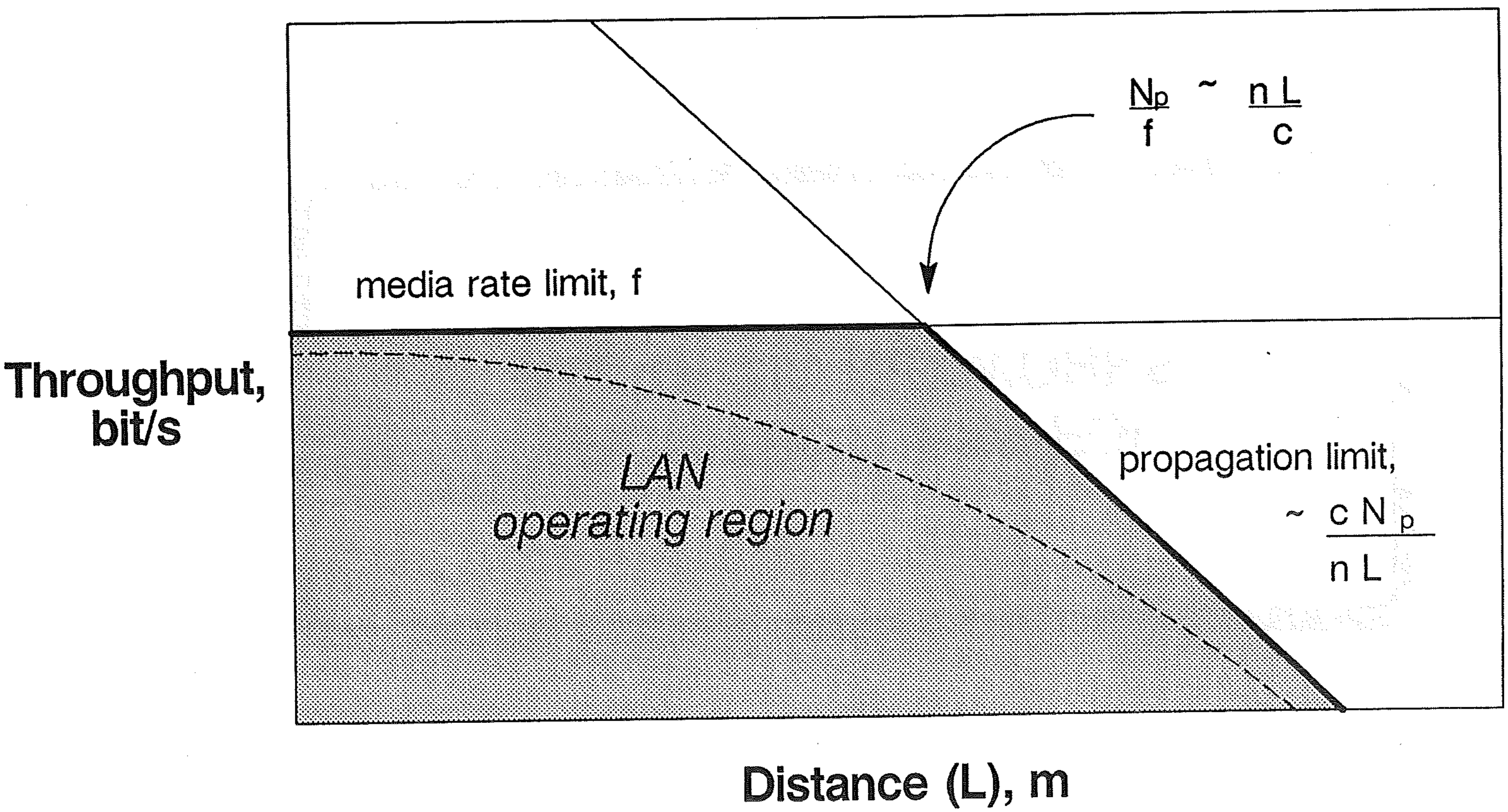
# FUNDAMENTAL TDMA PROTOCOL LIMITS

Conventional local area networks (of few km length) employ Time Division Multiple Access (TDMA) protocols to arbitrate fairly between users. Generally, these networks are limited by two mechanisms: one is the signalling limit on the channel imposed by the network interface components, and secondly, a protocol–dependent propagation delay limit that varies inversely to the length of the network. The latter comes about because TDMA protocols, whether it be ethernet or token rings, arbitrate fair use of the common channel by guaranteeing that each user (or node) will have an opportunity to talk during a given period. In effect, the bandwidth of the channel is distributed evenly among the users. A by-product of this is that a node must listen for a period equal to the propagation delay of the media between transmisions. Hence, if the packet size remains constant, the efficiency will decrease as the data rate increases. This suggests one reason why higher speed networks, such as FDDI or HIPPI, have defined larger packet sizes.

# FUNDAMENTAL TDMA PROTOCOL LIMITS




*Packet size must scale with bit rate to maintain high efficiency for "fair" protocols.*
*Suggests WAN strategies for > 100 Gbit/s – terabit local networks?*

# ARCHITECTURES FOR ALL-OPTIC NETWORKS

# SOME CANDIDATE ALL-PHOTONIC ARCHITECTURES

Two of the most prevalent all- or mostly- optic network systems being explored today are dense wavelength division multiplexing (WDM) and code division multiple access (CDMA). Both partition the optical spectrum into channels in order to circumvent the limited signalling rate of electronic components. With WDM, each channel operates on a separate wavelength. No provisions are made to implement protocols optically (this is typically done in a companion electronic network). With CDMA, the approach is slightly different in that all channels are encoded with a unique code that is spread over all wavelengths. Thus, each channel occupies all of the 10THz spectrum, but is non-interfereing with the others since it is orthogonal (by design). The net effect with CDMA is that the network behaves as a non-blocking crossbar switch. Furthermore, the CDMA encoding method can be based on phase encryption of the multi-wavelength front, which preserves optical power and makes the method amendable to fourier optics implementation and the possibility of adding boolean functions.

# SOME CANDIDATE ALL-PHOTONIC ARCHITECTURES

- Very dense WDM
- Fiber Optic Code Division Multiple Access (FO–CDMA)

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# POTENTIAL OPTICAL NETWORK PROTOCOLS

A few of the more widely known protocol functions that must be implemented by a network are regeneration, addressing, arbitration, error detection and correction, flow control, routing, and authentication. In an all-optical network, the order of some of these may in fact be altered due to the unusual properties of the spectral CDMA. For example, addressing and routing may be conducted before regeneration.

# POTENTIAL OPTICAL NETWORK PROTOCOLS

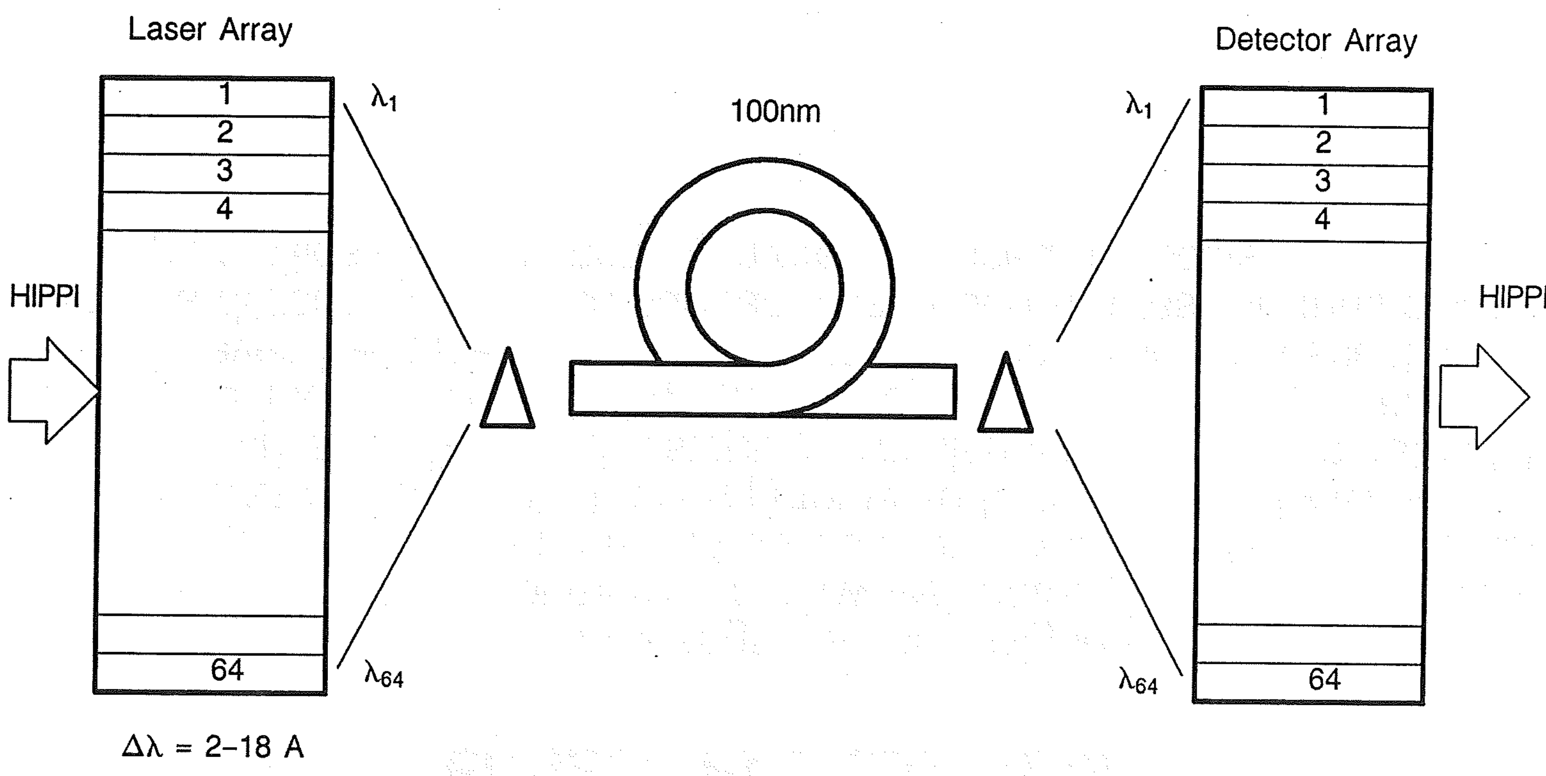
- Regeneration *
- Flow Control *
- Addressing
- Arbitration
- Routing (and Address Translation)
- Encryption
- Error Detection/Correction
- Authentication

* more difficult to implement optically

# DENSELY PACKED WDM

In dense WDM, one channel wavelength can be assigned to one service, e.g., voice, video, etc. Sixty-four or more of such wavelengths can be closely spaced and passed over a single-mode optical fiber at 1.55um. However, another method is to assign each bit of a computer word to an individual wavelength. Assuming each laser diode in the stepped wavelength array can operate at 1 Gbit/s, such a link could conceivably operate beyond 64 Gbit/s (for a 64 element array). However, because each laser operates incoherently with respect to the others, it is difficult to sum and subtract bits in boolean fashion thus closing many opportunities for implementing more advanced protocols.

# DENSELY PACKED WDM



# CDMA FOR CELLULAR TELEPHONE

Although spread spectrum communications has been used primarily for military communications for the last few decades, CDMA is now being used for commercial deployment of cellular telephone networks to squeeze more capacity out of the existing RF spectrum and to allow more rapid reconfiguration of the system and growth.

Los Angeles Times



# PacTel Cellular Takes a Gamble on Technology

■ **Telecommunications:** Mobile phone companies are adopting new systems. The Southland's biggest carrier has decided to go its own way.

By DEAN TAKAHASHI
TIMES STAFF WRITER

Jeffrey R. Hultman, president and chief executive of PacTel Cellular, likes to tell his employees that they are pioneers in a "100-year business."

Taking a long-term view keeps a decision such as which of two competing cellular phone technologies to adopt from seeming quite so daunting, he says. Even so, Hultman and other cellular industry executives are grappling with the biggest technological transition in the industry's brief history.

The change involves modernizing the nation's cellular networks with second-generation digital technology that will allow cellular companies to squeeze calls onto an already cramped wave band.

For PacTel Cellular, the nation's second-largest cellular phone company, the change comes at a crucial time. In Los Angeles, the Irvine-based company's largest market, the carrier that converts to digital first could capture the lion's share of subscrib-

# CELLULAR: PacTel Decides to Go Its

Continued from D1

and PacTel has a reputation for doing that."

Hultman said he was skeptical when officials from Qualcomm Inc., a San Diego start-up, approached him late last year and told him their digital technology—known as code division multiple access, or CDMA—would allow PacTel to squeeze 20 times more callers onto the existing network.

After all, just a few weeks earlier and at Hultman's recommendation, the Cellular Telecommunications Industry Assn. voted unanimously to adopt a digital technology called time division multiple access, or TDMA, ending a two-year dispute over industry standards. Because it emerged so late, CDMA was not considered.

TDMA extracts three to seven times more capacity from the existing analog system by slicing a frequency into a number of time slots. The transmitter bursts a signal for a call for a given period of time and then alternates to another call, dropping the first one for a split-second. The caller can't notice the gaps between the call signals because they are so short. In effect, several calls are handled simultaneously on the same frequency.

But CDMA systems, first developed by the military to protect radio communications, spread a number of call signals across the available frequency spectrum simultaneously and assign a unique binary code to each signal. The signals are sorted from the b...

next year. He cautions, however, that any further disputes over standards could delay industry growth and raise the cost of digital cellular equipment.

Some industry observers say PacTel and others who support CDMA are hurting the industry by not being team players and endorsing the industry standard.

"What is disturbing is that certain companies [that support CDMA] are so willing to pursue a panacea that isn't proven and wasn't part of the testing process that arrived at a standard," said Eric Lissakers, director of planning and development for Ericsson Radio Systems, a Richardson, Tex., cellular phone manufacturer. "They are looking at a rainbow instead of the planned evolution of a standard."

Mark Buford, a spokesman for Northern Telecom Inc., a Canadian telecommunications manufacturer, said his company has endorsed TDMA but continues to explore CDMA as an alternative. He said any changes could result in higher development costs and a delay in the conversion to digital.

For its part, the Federal Communications Commission ruled in 1987 that carriers do not have to follow a particular standard, so the choice between technologies could be made on a market-by-market basis.

But PacTel's Hultman argues that the advantages of CDMA technology are too big to ignore.

northern Orange County.

Today, PacTel has more than 170 cell sites covering 10,000 square miles in five Southland counties. Of the company's 440,000 subscribers, about 170,000 are in Los Angeles, estimates Herschel Shosteck, a cellular market researcher in Silver Spring, Md. About 40% of PacTel's Southern California customers are in Orange County.

The company's growth in Southern California reflects the enormous popularity of cellular phones in the land of car-crazy commuters and clogged freeways. And growth has been brisk in PacTel's other California cellular markets: San Francisco, San Diego and San Jose. PacTel provides cellular service in more than 20 cities, including Atlanta.

With 30 million potential subscribers in its coverage areas, PacTel Cellular is second only to McCaw Cellular Communications of Kirkland, Wash.

Nationwide, the number of cellular subscribers is expected to rocket from 3.5 million last year to at least 18 million by 1995, Shosteck estimates. About 10% of the nation's cellular phone subscribers are in greater Los Angeles, the nation's second-largest market after New York City.

PacTel has grown to more than 1,300 employees, including 535 in Orange County, and plans to add 300 more employees by year-end. Three weeks ago, it began moving its headquarters staff to new quarters in Irvine.

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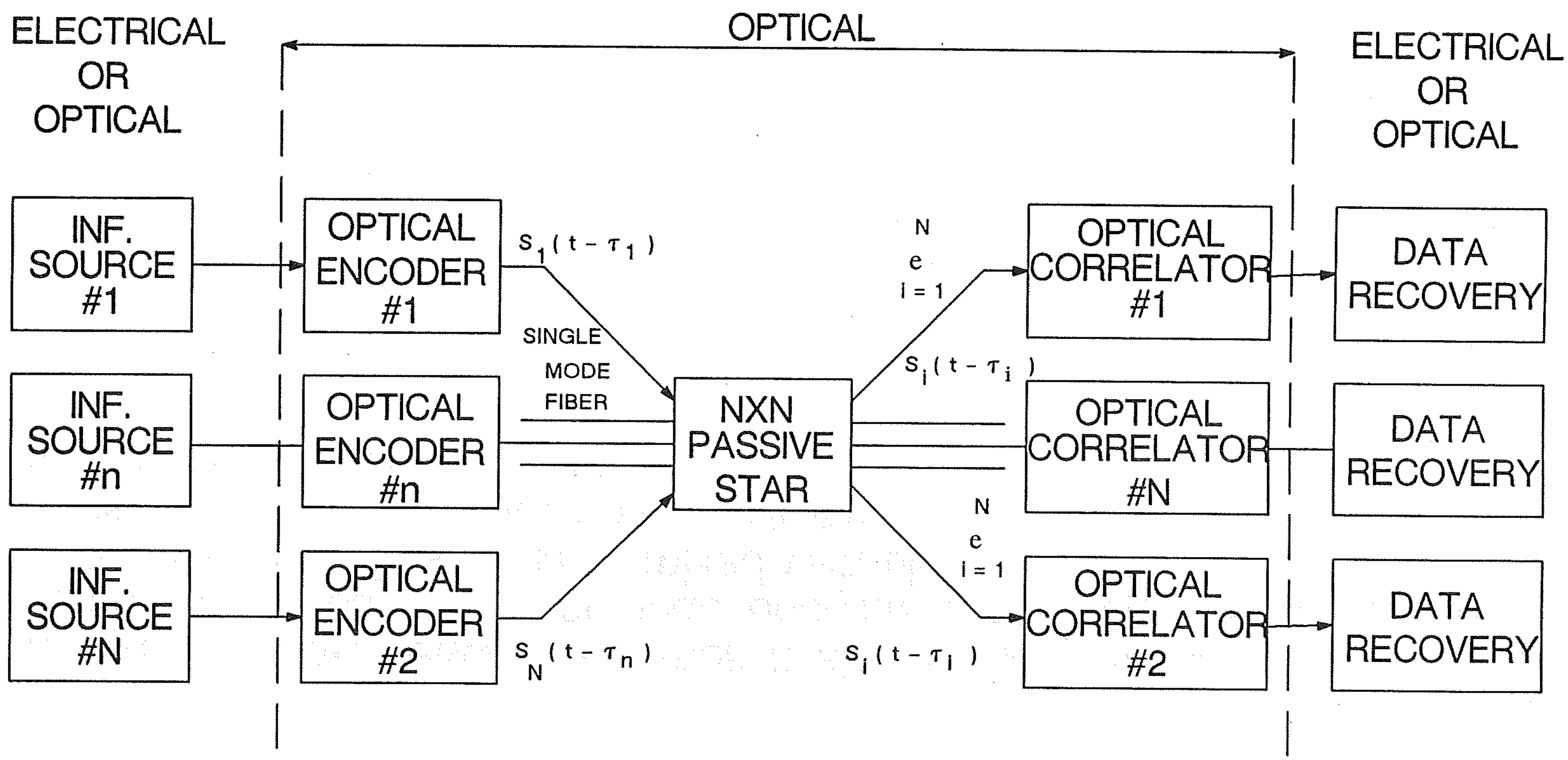
# FIBER OPTIC CDMA

The basic CDMA network assumes a star topology (although this can be altered) where each user or node encrypts a message using his specific orthogonal code. This signal is mixed with all others and re-distributed to all nodes on the network. Each network receiver then applies a key to filter out all other channels except the one of interest.

# FIBER OPTIC CDMA

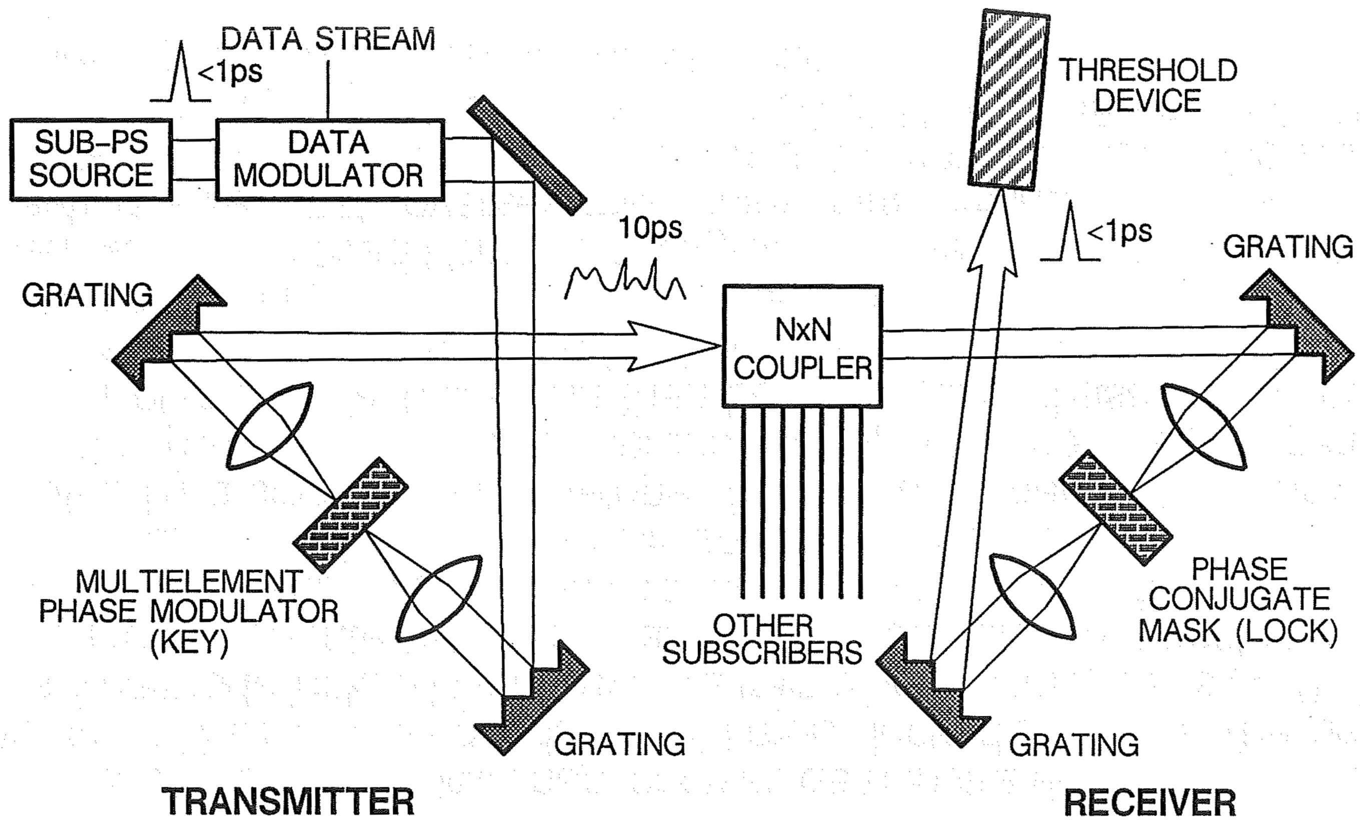



*Fiber optic code division multiple access (FO-CDMA) implemented in a STAR configuration (c.f., Salehi, 1987).*

# FIBER OPTIC CDMA

The first basic spectral CDMA network was demonstrated by Salehi, Brackett, and Weiner at Bellcore using a visible light mode locked dye laser. The idea is as follows. The mode locked laser delivers a train of very short pulses (<100fs) at a very high repetition rate (>1GHz) to an optical modulator. The host then drives the modulator to extinguish or pass bits of this train. A simple fourier analysis of this bit stream would suggest an RF spectrum resembling a comb function modulated by a $sinc^2$ power envelope. This signal is then passed through an optical grating and lens to spatially spread each spectral ine across a spatial light modulator element. Each line can then be individually phase moduated, 0 or 180 degrees, using the prescribed orthogonal code set and then recombined with another grating/lens assembly and sent out to the network. This specific channel can be retrieved from the background noise of the the other channels by creating a key that reverses the phase shifts originally introduced at the transmitter. All other channels are rejected. JPL is now extending this system to the minimum dispersion wavelength of optical fiber (1.55um), and building higher level protocols on top of this foundation.

# FIBER OPTIC CDMA




*Fiber optic code division multiple access (FO-CDMA) network uses freguency spreading rather than temporal spreading (c.f., Salehi, 1988).*

# OPTICAL ARBITRATION

Pure optical arbitration can be implemented in a receiving station using a secondary photorefractive mask. The first SLM mask is used to program the local station's address or a network broadcast address. The second mask is a photorefractive crystal programmed by the first source node able to write to it. Data flows from the source node to the destination node after the second mask is written. Other stations are blocked. Once complete, the receiver station erases the second mask allowing other source nodes to write to it. This approach has an advantage over hybrid optical/electronic approaches in that less handshaking is required between the nodes.

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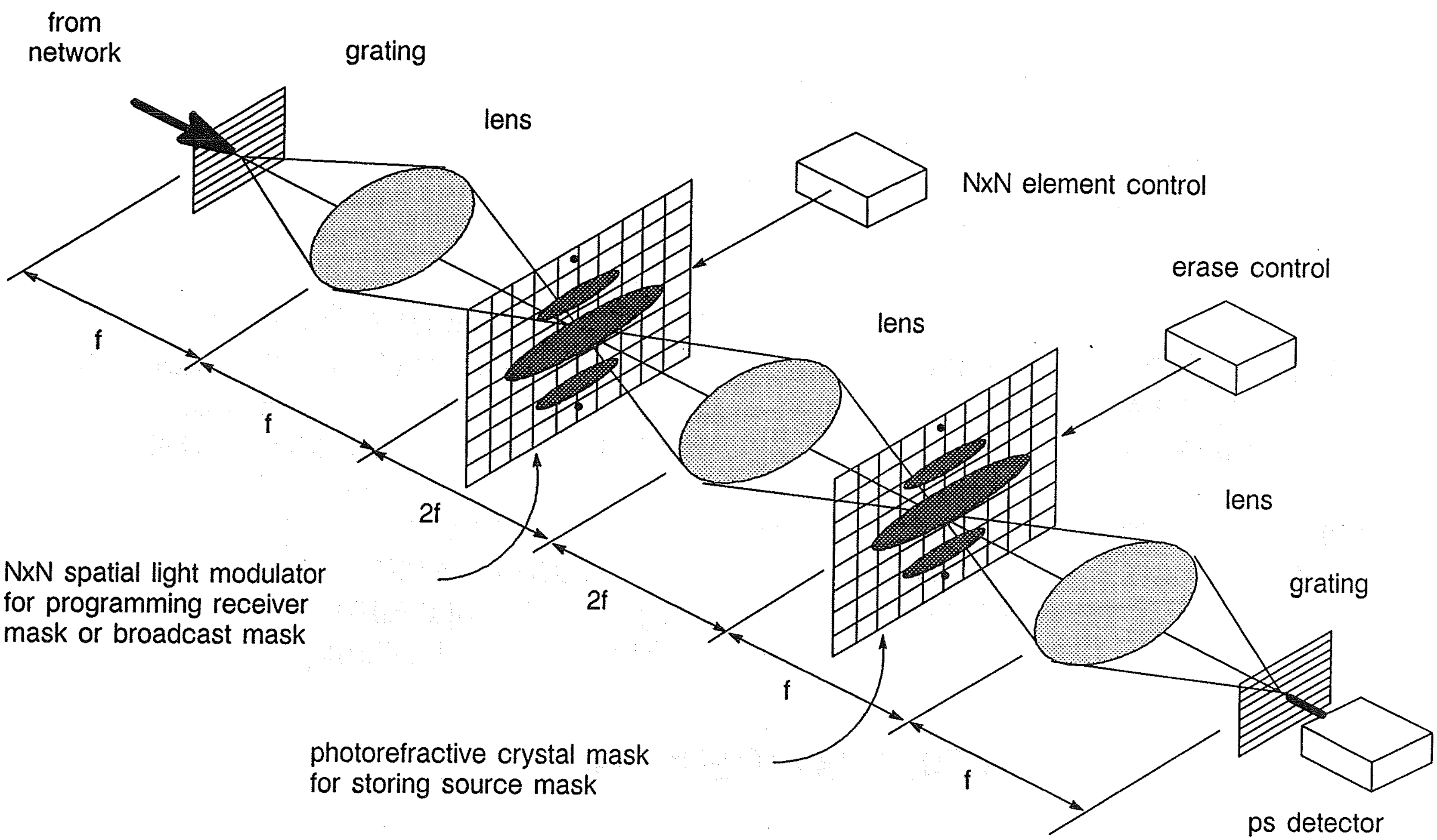
# OPTICAL ARBITRATION



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# OPTICAL SYSTEM POWER BUDGET

All the losses in any optical network must not exceed the difference between the transmitter power output and the receiver sensitivity. Since the spectral CDMA uses a mode locked laser, this power level can be quite high. However, it also has additional losses over the typical optical link, such as spatial modulator losses, coding losses, grating losses, and polarization correction losses. When all added up, these losses fall between the power budget for a coherent and incoherent transmission system. The system shown would support 32 users at 1 Gbit/s using a coherent detector.

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# OPTICAL SYSTEM POWER BUDGET

| | dBm | dBm |
|---|---|---|
| Source ($P_t$=1W) | +30 | |
| Receiver ($P_r$=2uW: non-coherent) | −25 | **55dB** |
| Receiver ($P_r$=20nW: coherent) | −45 | **75dB** |
| Optical Components: | | |
| gratings (4 x 85%) | −3 | |
| fiber coupling loss (3 x 1) | −3 | |
| fiber absorption loss (100m) | −1 | |
| star coupler division loss (32x32) | −15 | |
| SLM absorption loss (2 x 10%) | −20 | |
| Modulation Effects: | | |
| bandlimiting effects | −10 | |
| CDMA channel interference (n=10) | −10 | |
| TOTAL SYSTEM LOSS: | | **62dB** |

CONCLUSION: Sufficient power budget is available for femtosecond CDMA, especially if optical fiber amplification is used.

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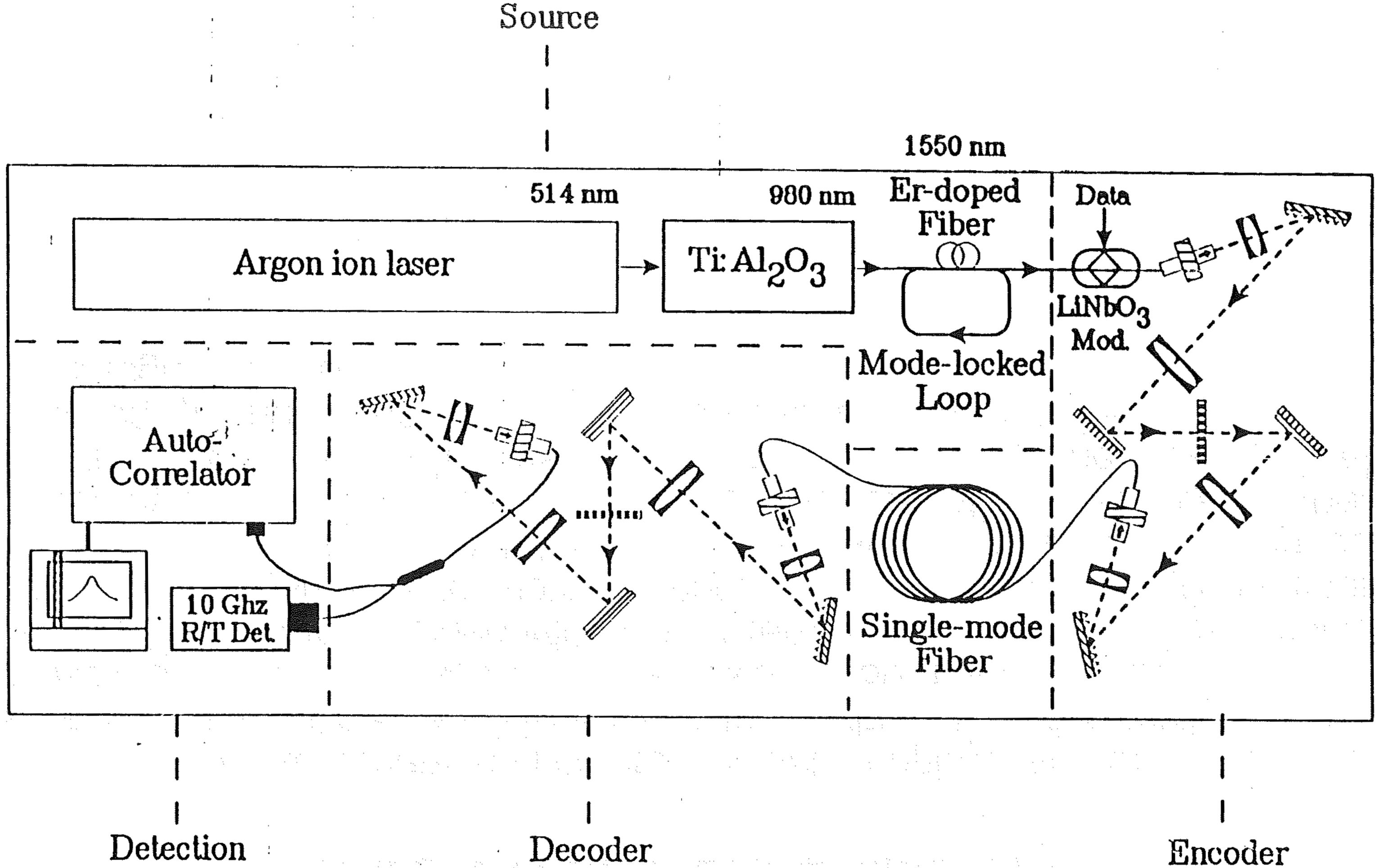
# LABORATORY EXPERIMENT

The laboratory experiment constructed at JPL employs an Argon pumped Ti:sapphire laser that delivers 980nm/20W to an erbium fiber ring cavity that is in turn excited to lase and passively mode lock at 1.55um/50MHz. Pulses as short as 700-fs have been obtained with this system and further reduction in pulse width (which translates into more channels) is possible with additional fiber compression stages. In the future, the bulky Argon pump laser could be replaced by a small cm–size semiconductor laser operating at 980nm. Further integration should permit the laser, its mode locker cavity, the data channel modulator, gratings, lens, and spatial light modulators to all be put onto the same integrated optic chip.

# Optical Protocols Lab. Set-up




P.L. Chua
Nov. 1, 1990

JPL

# TECHNOLOGY AVAILABILITY

Since spectral CDMA is only in its earliest stages of development leading toward a concept demonstration, many evolutionary steps are envisioned before an actual commercial system could be built. However, even at this early stage, some trends may be identified that would maximize technology insertion potential by stages into a large system such as space station. For example, in the near term the baseline design calls for 100 Mbit/s FDDI network. A natural (interim) second step that would preserve all the existing system interfaces would be to pack more FDDI channels into the same optical fiber using dense WDM techniques, which is expected to mature earlier than CDMA. Many of the gratings, micro lenses, and couplers used in WDM would also be needed in the spectral CDMA, and so, such a step would allow early returns of R&D investment in more fundamental devices needed for WDm and CDMA systems. A final step would be to migrate to full spectral CDMA which would allow individual interfaces to be elevated to beyond 100 Gbit/s and new forms of services to be added.

# TECHNOLOGY AVAILABILITY

- **BASELINE CAPABILITY (NOW)**
  - NET: dual-redundant (Class A) 100 Mbit/s token ring (FDDI)
  - CABLE: multi-mode fiber optics
  - CONNECTORS: multi-mode tolerance components
  - TOPOLOGY: 38 concentrators x 8 ports = 304 users (ring)
  - SOURCE: LED or laser diode
- **INTERIM (FY'96)**
  - NET: multiple FDDI rings WDM–muxed onto single fiber (5Gbit/s)
  - CABLE: single-mode and multi-mode fiber optics
  - CONNECTORS: single-mode tolerance components
  - TOPOLOGY: multiple rings through patch panel
  - SOURCE: 16–64 element laser diode stepped $\lambda$ array
- **LONG TERM (FY'01)**
  - NET: all-photonic CDMA crossbar (>100Gbit/s)
  - CABLE: single-mode dispersion flatten fiber optics
  - CONNECTORS: single-mode tolerance components
  - TOPOLOGY: multiple logical rings, star, or mesh
  - SOURCE: integrated optic mode-locked laser & modulator

JPL

# BASELINE INTEGRATION

This effort will ultimately produce a two–node laboratory demonstration that will interface two forms of services (e.g., image streams and computer packet). It is planned to develop an interface to the DMS testbed at ARC to fully assess space station requirements and performance benchmarks with this new generation of network. Three basic groups of tests are planned, including functional system interface requirements, network performance, and mechancial interfaces. The effort also draws upon integrated optic component reserach development efforts at JPL and elsewhere.

JPL

# BASELINE INTEGRATION

- Interface with ARC DMS testbed
- Functional assessment
- Performance assessment
  - NIU power consumption
  - optical power budget
  - protocol latency and speed
  - number of channels
  - error rate
- Mechanical interface assessment
  - size
  - weight
  - topology

JPL

# NEW COMPONENTS REQUIRED

A variety of new components are required to fully realize such a system commercially. Some of thse devices include coherent fiber optic media, couplers, star splitters, and modulators), mode locked lasers on a chip, fast (1Gbit/s) 1D spatial light modulators, and fast picosecond detectors to name a few. Some are actually not too difficult to fabricate, but they need sufficient impetus to spark interest among semiconductor device physicists...which is one of the objectives on this effort.

# NEW COMPONENTS REQUIRED

- Coherent fiber optic components (media, couplers, splices, modulators)
- Tunable sources and detectors – in large arrays (MQW)
- Monolithic femtosecond optic generating sources
- Fast planar 1D SLMs
- Low–repetition rate (<10GHz) real–time femtosecond detectors
- Optically controlled switches
- Optically controlled wavelength tuning
- Fast high-level protocol engines (>>Gbit/s TCP/IP)

JPL

# SUMMARY

Optical protocols for networks provides a way of bypassing the electronic bottleneck and allowing speeds of 100 Gbit/s or more to be achieved. In principle, both stream and packet services can be conveyed over the same transmission fabric with no centralized control. The spectral CDMA technique described here provides the foundation for implementing basic boolean functions to build higher level network protocols such as arbitration, routing, and error detection. A natural by-product of the system is that it provides full non-blocking crossbar connectivity. Because the basic interface is all optical and switched at some sub-multiple of the actual channel, little electrical power is consumed by the network in the standby or active modes. As data rates increased, such a difference could become quite large.

JPL

# SUMMARY

## ADVANTAGES OF OPTICAL PROTOCOLS

- No electronics limit...
  - clock recovery independent of data format
  - synchronous or asynchronous operation
- Addressing, routing, encryption possible in the optical domain
- Crossbar connectivity
- Higher throughput efficiency (no one NIU limits aggregate capacity)
- Ideally suited for real–time stream traffic (voice, video, SAR)
- High security
  - difficult to tap by any direct optical methods
  - tapping is detectable at network receivers
  - movement of media is detectable during *power-off* periods
- Channel signalling rate limited by optical modulator to >20GHz

# ADVANCED
# CREW PERSONAL SUPPORT COMPUTER (CPSC)
# TASK

PRESENTED BY:
DEBRA MURATORE, JSC

SPACE STATION EVOLUTION '91
8/7/91

# ADVANCED CREW PERSONAL SUPPORT COMPUTER (CPSC) TASK

- BACKGROUND
- OBJECTIVES OF TASK
- BENEFITS TO SPACE STATION PROGRAM
- TECHNICAL APPROACH
- BASELINE INTEGRATION
- GROWTH AND EVOLUTION OPTIONS
- SUMMARY





D. Muratore 8/7/91

# BACKGROUND

- NECESSARY TO FREEZE COMPUTER DESIGN EARLY
- LEADING EDGE TECHNOLOGY NOT ALWAYS FEASIBLE - RISK
- DISADVANTAGES OF OLDER TECHNOLOGY
  - INCREASED MAINTENANCE COSTS
  - CANNOT EXPLOIT NEWER TECHNOLOGIES
- 30 YEAR MISSION OF SPACE STATION FREEDOM
- FITTING MISSION REQUIRED SOFTWARE INTO LIMITED SHUTTLE COMPUTERS

# OBJECTIVE

- PROCESS TO INTRODUCE NEW COMPUTER TECHNOLOGY INTO SSFP
- AUGMENT CORE COMPUTER CAPABILITIES TO MEET ADDITIONAL MISSION REQUIREMENTS
- MINIMIZE RISK IN UPGRADING TECHNOLOGY
- PROVIDE LOW COST WAY TO ENHANCE CREW AND GROUND OPERATIONS SUPPORT

# BENEFITS

- TESTING IN PLACE INCREASES CONFIDENCE IN NEW TECHNOLOGY
- ISOLATION FROM CORE COMPUTERS PERMITS RAPID DEPLOYMENT OF NEW CAPABILITIES
  - FAULTS NOT PROPOGATED FROM CPSC TO CORE COMPUTERS
- SYSTEMS REMAIN CURRENT WHILE TAKING ADVANTAGE OF STATION'S CAPABILITIES
- MAINTAINS DEGREE OF TESTING AND RELIABILITY
- PREVENTS TECHNOLOGICAL OBSOLESCENCE

# TECHNICAL APPROACH

- PHASE 1
  - MACINTOSH-BASED OBJECTIVES
  - RAPID PROTOTYPING TO DEVELOP REQUIREMENTS
  - CONVENIENT DEVELOPMENT PLATFORM
- PHASE 2
  - CPSC (DMS COMPATIBLE) OBJECTIVES
  - BUILDS ON PHASE 1 REQUIREMENTS
  - PROTOTYPE INCREMENTAL BLOCK HARDWARE

# PHASE 1 ACTIVITIES

- DTO 1206 (STS-41 11/90) AND DTO 1208 (STS-43 8/91)
- CURSOR CONTROL DEVICE EVALUATION
  - 1.25" BUILT-IN TRACKBALL
  - OPTICAL MOUSE
  - 2" TRACKBALL WITH RESTRAINT RAIL
  - THUMBALL DEVICE
  - FELIX
- ADVANCED APPLICATIONS
  - WORLD MAP
  - ELECTRONIC FLIGHT DATA FILE (HYPERMEDIA)
  - ELECTRONIC MAIL
  - CREW ALARM MESSAGING

# PHASE 2 ACTIVITIES

- PROTOTYPE HARDWARE AND SOFTWARE
- MODULAR PACKAGING TO PERMIT GROWTH AND EVOLUTIONARY PERFORMANCE UPGRADES
- EMPHASIS ON COMPATIBILITY WITH SPACE STATION FREEDOM DATA MANAGEMENT SYSTEM
- POTENTIAL SPINOFFS FROM DARPA'S STRATEGIC COMPUTING PROGRAM AND HIGH DEFINITION SYSTEMS PROGRAM
- DEMONSTRATION AND EVALUATION OF PROTOTYPES AS SPACE SHUTTLE PROGRAM (SSP) PAYLOADS

# BASELINE INTEGRATION

- OPERATIONS DATA FILE
  - CREW ANNOTATION
  - HYPERMEDIA LINKING OF INFORMATION
  - STORAGE OF REFERENCE INFORMATION
  - ONLINE HELP

- ELECTRONIC MAIL/ DATA TRANSFER VIA VOICE CHANNEL OR DATA MANAGEMENT SYSTEM

- PAYLOAD SUPPORT
  - DATA ANALYSIS SOFTWARE (NON-REALTIME)
  - REALTIME DATA COLLECTION AND DISPLAY

# GROWTH AND EVOLUTION OPTIONS

- CREW PERSONAL SUPPORT COMPUTER
  - PAYLOAD GENERAL SUPPORT COMPUTER FULFILLS THIS ROLE IN SSP BUT CURRENT HARDWARE WILL BE OBSOLETE BY SSFP FIRST ELEMENT LAUNCH
  - WORD PROCESSING AND SPREADSHEET
- CREW ALARM MESSAGE FUNCTION
- WORLD MAP

# GROWTH AND EVOLUTION OPTIONS

- REMOTELY COMPUTED DISPLAYS
  - APPLICATION PROCESSING ON GROUND DISPLAYED ONORBIT VIA DATA TRANSFER CAPABILITIES
  - NO IMPACT TO CORE SYSTEMS IF VOICE CHANNEL USED
- HIGH DEFINITION IMAGING APPLICATIONS
  - STATION ASSEMBLY
  - STATION MAINTENANCE
  - CREW HEALTH CARE
  - EARTH OBSERVATION

# ISE Advanced Technology

## Space Station Evolution
## Beyond the Baseline

August 6-8, 1991

Barry R. Fox
McDonnell Douglas Space Systems Co.

# Scheduling is Hard

- The true nature of a project is not always immediately obvious!

# Scheduling is Hard

- Space Station scheduling problems are diverse
  - Assembly Plan
  - Flight Manifest
  - Avionics
    - development
    - test
    - integration
  - Training
    - Shuttle Astronauts
    - Station Astronauts
    - Control Center Operators
    - Integrated Training
  - Facilities
    - Shuttle Simulators
    - Zero-G Simulators
    - Tele-Robotics Simulators
    - Avionics Development Facility

# Scheduling is Hard

- Space Station scheduling problems are diverse
  - Station Operations
    - Core processes
    - Payloads
    - Real-time schedule evaluation & revision
  - Ground Operations
    - Control Center staffing
    - Payload Operations
  - Publications
    - Flight Plans
    - Schedules

# Scheduling is Hard

- It is difficult to build purely automated scheduling systems
  - It is impossible to reduce our measure of a good schedule to one number that can be used in our search for an optimal schedule:
    - Everyone has different opinions
    - Our priorities depend upon circumstances
  - All algorithms that attempt to find a good or optimal schedule are based upon search:
    - Even familiar algorithms, for instance square root, are based upon search.
    - However, in scheduling problems the time required to solve a given problem increases exponentially with the number of activities and resources to be scheduled.

# Scheduling is Hard

- It is difficult to build interactive scheduling systems
  - The implementation of interactive scheduling systems requires a disproportionate investment in the graphical user interface.
    - Estimates now range between 40 and 60 percent of effort.
    - The effort required is likely to increase as user expectations become elevated.
  - User interface standards are rapidly evolving.
    - A standard without concensus is not a standard.
      - Windows 3.0
      - Macintosh
      - X-Windows
      - OpenWindows
      - Motif

## Scheduling is Hard

- Familiar, commercial project scheduling software cannot effectively handle the complex "resource constrained" and "state constrained" scheduling problems that are characteristic in the Space Station domain.
- Commercial, off-the-shelf products are not generally available in source code for customer modification.

# Scheduling is Hard

- State-of-the-art scheduling research performed at the various NASA centers, including JPL, NASA-ARC, GSFC, and in the research laboratories of the major NASA contractors, including McDonnell Douglas, Martin-Marietta, and Lockhead, is based upon LISP
  - LISP is not generally accepted for production operations.
  - The data structures and algorithms are not easily translated into conventional languages.

# Scheduling is Hard

- Extrapolation from the level-of-effort required to support Space Shuttle opeations, indicates that the level-of-effort required to schedule Space Station operations will be extremely challenging.

# Background

- January 1989
  - Three Tasks
    - Develop generic planning and scheduling technology ( NASA HQ, Code MD)
    - Develop technology that will enable real-time, onboard, schedule evaluation. (NASA HQ, Code MT)
    - Investigate technology that will enable real-time, onboard, schedule revision (MDSSC-SSD, WP-2)
  - Synergistic Combination
    - A full-function scheduler requires both schedule evaluation and revision.
    - Schedule evaluation requires generic scheduling technology
    - Schedule revision requires generic scheduling technology and schedule evaluation technology

## Background

- Prior to 1989
  - Prototype, interactive, "job-shop" scheduler
    - Wedge
    - LISP
    - Symbolics, 3600 family of computers
  - McDonnell Douglas Research Laboratories, IRAD

# Objective

- Develop and Demonstrate advanced scheduling techniques targeted towards SSF applications
  - Develop a library of scheduling software
    - Written in Ada with an X-Windows user interface
    - That supports both interactive and autonomous scheduling
    - That is generic, yet suitable for the development of specialized applications
  - Demonstrate the capabilities of this software in an interactive scheduling system
  - Develop the peripheral systems that will enable this software to become a stand-alone, turn-key, off-the-shelf product.

# Benefits

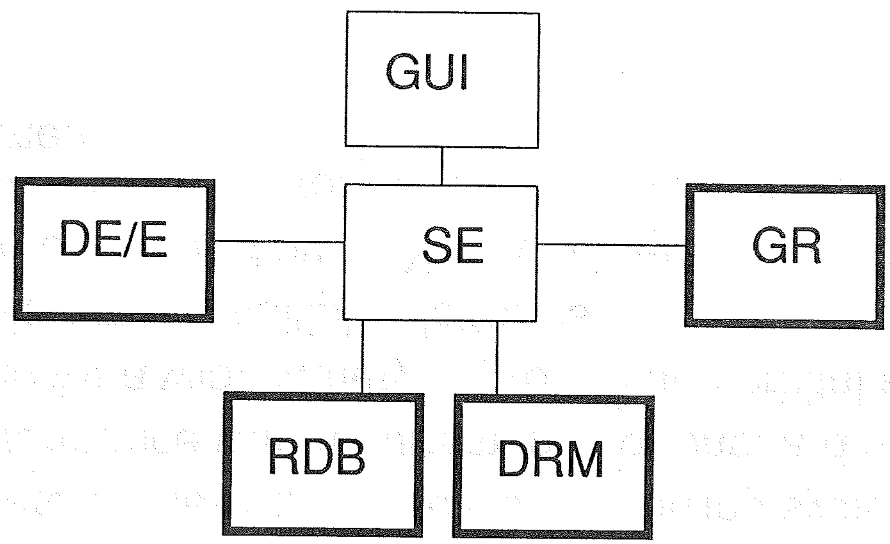
- Increased Productivity
  - By the groups that perform scheduling
- Increased Utilization
  - Of the people, resources, and facilities being scheduled
- Cost Avoidance
  - Avoid the staffing increases that may be necessary when station becomes fully operational.
- Enhanced Safety
  - Scheduler can guarantee that the resulting schedules satisfy all relevant contraints
  - Evaluator can guarantee that constraints remain satisfied at execution time.

# Benefits

- NASA owned, state-of-the-art, interactive scheduling system
  - that is in conformance with requirements for onboard systems
  - that is suitable for a wide variety of ground and orbital applications
  - that is portable across multiple platforms
  - that can be freely shared by all NASA centers and contractors
  - that can serve as a cost-effective platform for continuing research and development

# Approach

- Architecture
  - Centralized Scheduling Engine
  - Distributed Resource Managers
  - Graphical User Interface
  - Interactive Data Entry, Editting
  - Graphical Reports
  - Relational Database Connections



# Approach

- Scheduling Engine
  - Incremental Scheduling
    - provides the ability to create or edit the schedule by scheduling and unscheduling one item at a time
  - Non-Chronological
    - provides the ability to create or edit the schedule in much the same way that you might draw and erase I-beams on a piece of paper.

# Approach

- Graphical User Interface
  - Current User Interface
    - Based upon X-Windows
    - Enables remote execution
      - Macintosh with X-Windows at JPL
      - Scheduling engine in Houston
  - Next Generation User Interface
    - GENESIS
      - GENEric Scheduling Interface System
    - Jointly designed with JPL
    - Based upon X-Windows
    - Will become a seperate product that can be used by a variety of scheduling engines and applications.
    - Based upon the most general concepts of interactive scheduling.

# Approach

- Software Engineering
    - This software is has been designed for distribution and re-use:
        - Modular (packages)
        - Data Abstraction
        - Information Hiding
        - Side-Effect Free
        - Advanced Data-Driven Testing
        - With emphasis on
            - portability
            - maintainability
            - reusability
            - adaptability

## Approach

- NASA ownership
  - Periodic contribution to COSMIC
  - Available directly from the Software Technology Branch
- NASA wide collaboration
  - New user interface was designed through a series of video conferences with JPL
  - Standards for data interchange will be developed through a similar effort
  - Work on distributed resource managers continues with the collaboration of the the COOPES development team
  - Planning is nearly complete for the second Planning and Scheduling workshop to be held September 24-26, whose purpose is to chart a program of cooperative research and development

# Baseline Integration

- Actively working with several customers
  - COMPASS is being used to build schedules and resource profiles for the Design Reference Missions.
  - COMPASS has been selected as the basis for ADF and MRMDF scheduling.
  - COMPASS is being evaluated for use in several other application areas including:
    - Space Station Training Office
    - Systems Engineering Simulator
    - Ground Operations Support

# Growth and Evolution

- Current Capability
  - provides reasonable, but approximate models of activities and resources
- Development of Advanced Technology is needed to realize the the full potential of the Space Station and supporting groups
  - Interruptable Activities with Persistent Resource Requirements
  - State Constrained Scheduling
    - Methods for accomodating change-over-costs (required for the ADF)
    - Methods for maintaining state-transition time-lines and for scheduling against required conditions.
  - Schedule Optimization
    - Genetic Algorithms
  - Parallel Scheduling Algorithms
    - Pipelined Networks of Transputers

# Growth and Evolution

- Advanced Applications
  - Distributed Resource Management
    - Enables the creation of high fidelity resource models
    - Enables access to resources managed at remote sites
    - Research performed cooperatively with the COOPES development team.

# Growth and Evolution

- Advanced Applications
  - Distributed Scheduling
    - Geographically Distributed
      - Simultaneous access to central scheduler
      - Simultaneous operation of multiple schedulers with centralized data
      - Simultaneous operation of multiple schedulers with multiple sources of data

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# Growth and Evolution

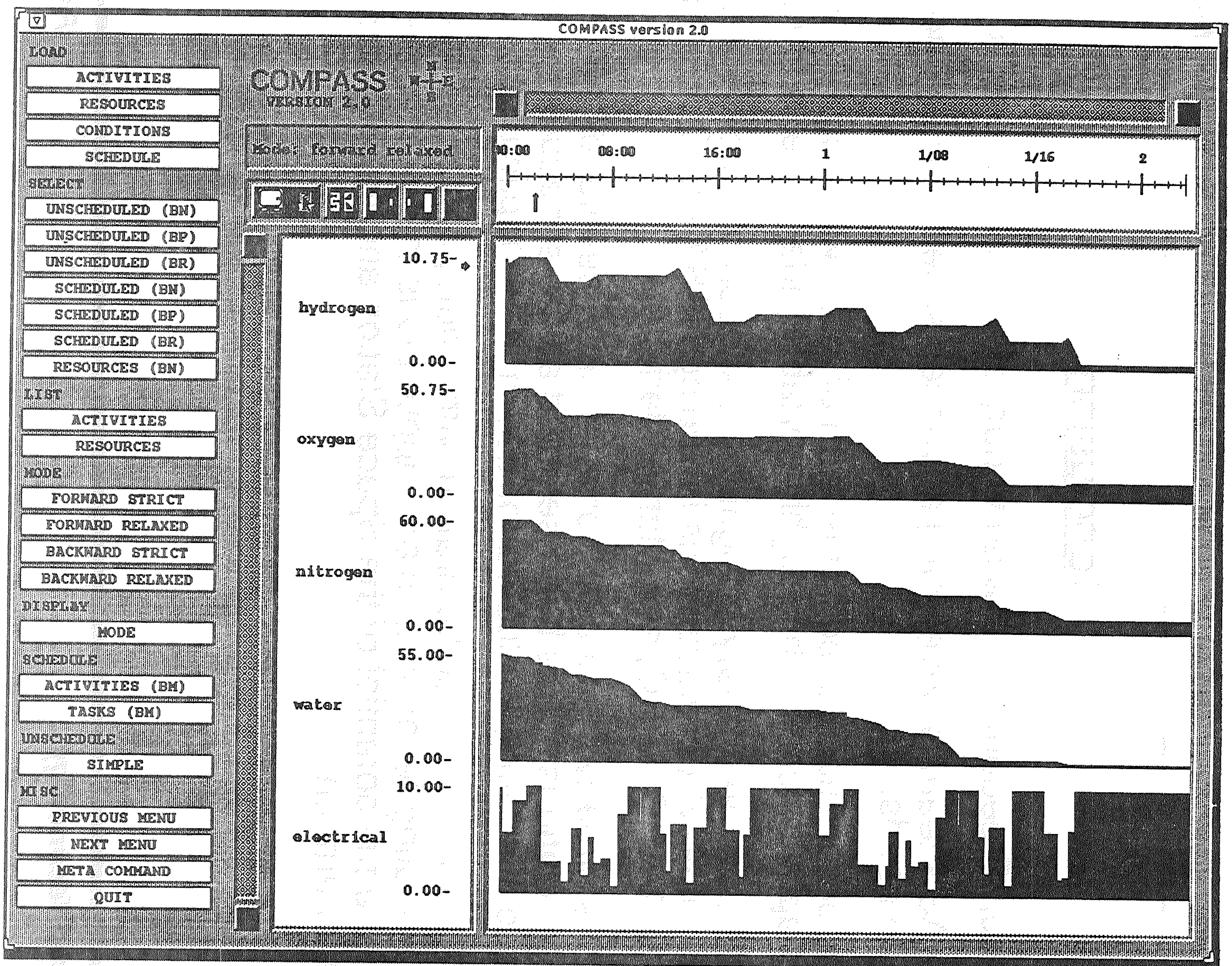
- Advanced Applications
  - Time-phased scheduling
    - Seamless integration of several phases of scheduling
      - Manifiest
      - Long-Term
      - Short-Term
      - Onboard/Detail

# Growth and Evolution

- Advanced Applications
    - Real-Time
        - Evaluation
        - Propagation of delays
        - Interactive and Autonomous Revision

# Conclusion

- Space Station Freedom has a wide variety of scheduling needs.
- The COMPASS team is developing advanced scheduling technology to satisfy these needs.
- This technology is maintained in the form of a software library and interactive scheduling application which is highly portable, adaptable, and re-useable.
- COMPASS is the beneficiary of significant support and collaboration from many different NASA organizations including NASA-HQ CODE MT, MD, and R, JPL, NASA-ARC, LeRC, and Martin-Marietta.
- COMPASS is already being used for analysis in several different Space Station organizations, it has been selected as the scheduler for two critical facilities, and it is being evaluated for use in other applications.
- The COMPASS team, in collaboration with others, continues to develop specific scheduling technologies and applications that are necessary in order to achieve the full potential of the Space Station and the organizations that support its operation.

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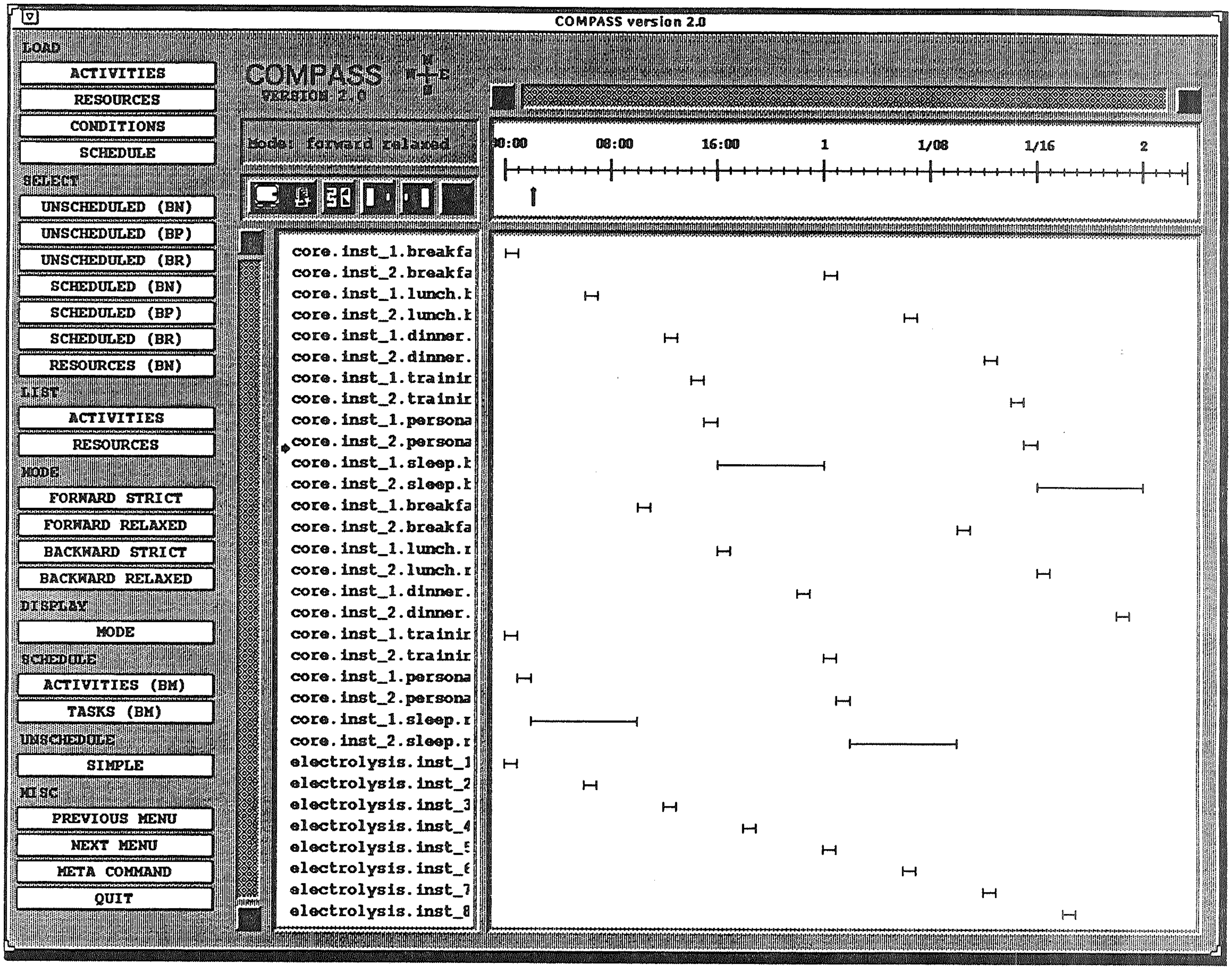
COMPASS version 2.0
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# Real Time Data System (RTDS)

- Background
- Technologies/Techniques
- Data Flow
- Shuttle Operations
- Pacing Factors
- Technology Gap
- Lessons Learned
- RTDS for Space Station Freedom

Troy A. Heindel/NASA/JSC/DF24

# Background

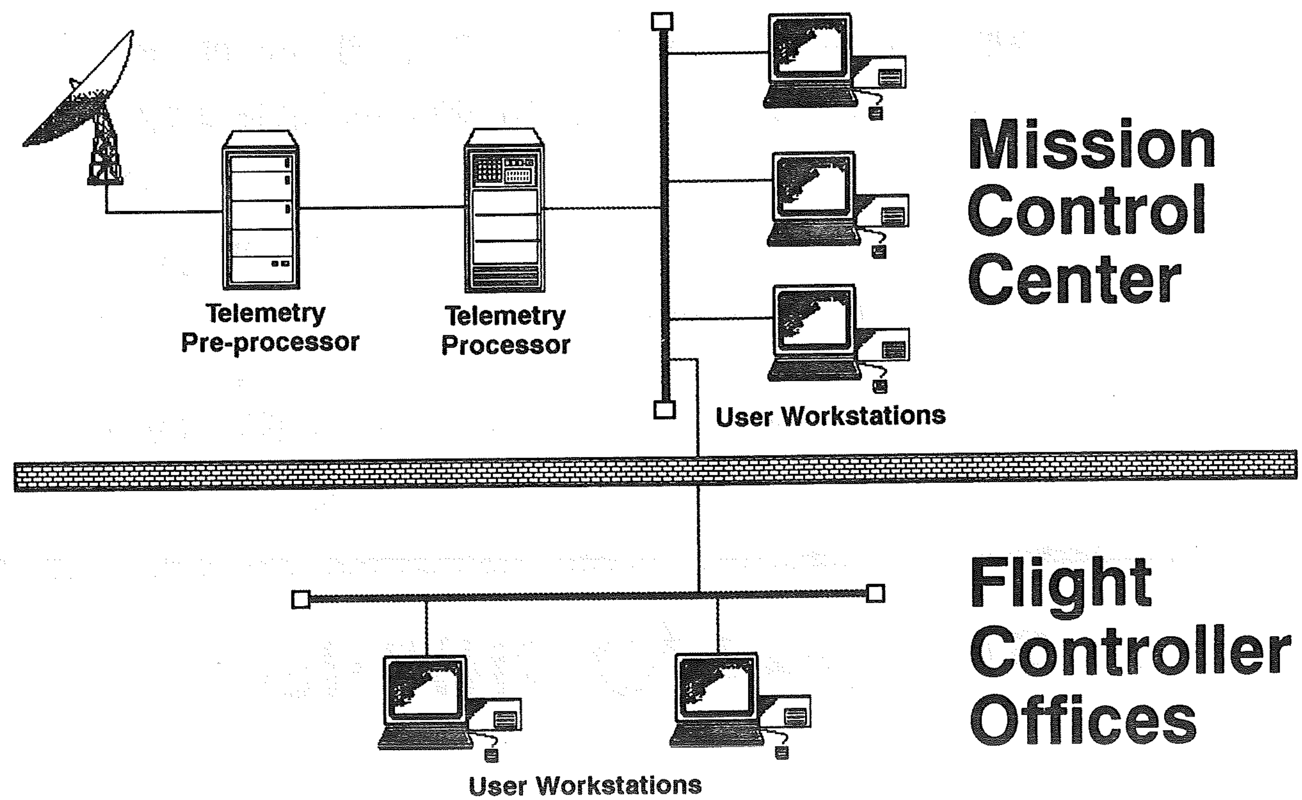
- Started in 1987 as RTOP from Office of Aeronautics, Exploration and Technology to demonstrate readiness of expert systems technology to perform in real operational environments
- Expanded in 1991 to provide office-based development, test, and training environment for Space Shuttle flight controllers

Troy A. Heindel/NASA/JSC/DF24

# Technologies/Techniques

- COTS Telemetry Processor
  - LowCost
- Unix, C, X-Windows, MOTIF, TCP/IP, NFS
  - Large base of expert programmers
- COTS Expert System Tool
  - User Developed Software
- Iterative Prototyping
  - vs. ABC Requirements

# Data Flow




Troy A. Heindel/NASA/JSC/DF24

# Shuttle Operations

- Integrated Communications Office (1987-present)
  - All traditional mainframe computations and displays in workstation
  - Additional fault detection programs not in mainframe
  - DATACOMM Expert System
- BOOSTER
  - All mainframe computations and displays in workstation
  - Additional fault detection programs not in mainframe
- Mechanical Systems (1988-present)
  - Program to automatically monitor orbiter tire pressures
- Guidance, Navigation, and Control (1989-present)
  - Jet-Control Expert System to monitor 38 primary RCS jets

Troy A. Heindel/NASA/JSC/DF24

# Shuttle Operations

- Remote Manipulator Systems (1989-present)
  - Position Monitor color graphics animation to show position of RMS
- Electrical, Generation and Illumination (1990-present)
  - Fuel Cell Expert System to monitor orbiter power generation systems
- FlightDirector(1990-present)
  - Wind Monitoring System to monitor cross winds at landing sites
- Data Processing Systems (1991)
  - DDMAT Expert System to monitor GPC configuration

# Pacing Factors

- New Technology Motivates Changes In Organizational Responsibilities
  - This results in turf wars
- Risk To Change
  - Still no flight critical workstation applications
- New Technology Systems, When Utilized On A Large Scale, Require Fundamental Changes In Management Philosophies

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# Technology Gap

- Over Twenty Years Of Main Frame Experience
- Less Than Five Years Of Workstation Experience
- Important Differences Between The Two Platforms
  - System Architecture (Centralized vs. Distributed)
  - Functionality

Troy A. Heindel/NASA/JSC/DF24

# Technology Gap

- Development Methodology
- Software Configuration Management
- Role of the User (in application software development)
- Relationship between main frame and workstation (tightly coupled?)

Troy A. Heindel/NASA/JSC/DF24

# Lessons Learned

- Find A Customer Who Wants And Needs The Technology
  - RTDS worked because it was customer driven
- Data Acquisition Is Key To Success Of Expert Systems
  - RTDS continues to spend 40% of resources on data acquisition
- Get Into OPS Location As Soon As Possible
  - Experience from operational use is most important

Troy A. Heindel/NASA/JSC/DF24

# Lessons Learned

- Be As Stand-Alone As Possible
  - Dependence on other systems is a liability
- Success Is Not Hampered By Mission Criticality Of Applications
  - Users were highly motivated to produce highly reliable systems
- Data Systems Architecture Must Support Rapid Changes
  - A key advantage over traditional data systems

Troy A. Heindel/NASA/JSC/DF24

# Lessons Learned

- Once In Operations, Reliability Is Most Important
  - User confidence hinges on system availability

Troy A. Heindel/NASA/JSC/DF24

# RTDS for Space Station Freedom

- Demonstrated Utility Of Automated Monitoring Systems In Shuttle
    - Increased importance in Station program
- Integrated Shuttle Telemetry With SAMMI/FRED Display Builder
- RTDS Is The Development Platform For Mission Control Center Upgrade (MCCU)
    - Demonstrated applicability for Station

Troy A. Heindel/NASA/JSC/DF24

# RTDS for Space Station Freedom

- Flight Controller Can Now Monitor Shuttle Operations From The Office
  - Possible cost-savings for on-going Station operations
- RTDS Provides For Stand-Alone Flight Controller Training
  - Space Station training personnel are investigating this for use in training Station flight controllers

# Computer System Evolution Requirements For Autonomous Checkout of Exploration Vehicles

Second Symposium on the Evolution of Space Station Freedom

August 6 - 8, 1991
League City, Texas

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# Agenda

- ❑ Overview of Advanced Automation Study
- ❑ Overview of Autonomous Diagnostic Checkout Task
- ❑ Assumptions
- ❑ Analysis Methodology
- ❑ Results
- ❑ Summary of Requirements for Autonomous Diagnostic Checkout
- ❑ Recommendations for Additional Analysis

# Overview of Advanced Automation For In-space Processing Study

This study, now in its third year, has had the overall objective and challenge of determining the needed Hooks and Scars in the initial SSF system to assure that On-Orbit assembly and refurbishment of Lunar and Mars spacecraft can be accomplished with the maximum use of automation possible. In this study automation is all encompassing and includes physical tasks such as parts mating, tool operation, and human visual inspection, as well as non-physical tasks such as monitoring and diagnosis, planning and scheduling, and autonomous visual inspection. Potential tasks for automation include both EVA and IVA events. A number of specific techniques and tools have been developed to determine the ideal tasks to be automated, and the resulting timelines, changes in labor requirements and resources required. The Mars/Phobos exploratory mission developed in FY89, and the Lunar Assembly/Refurbishment mission developed in FY90 and depicted in the 90 Day Study as Option 5, have been analyzed in detailed in recent years. The complete methodology and results are presented in FY89 and FY90 final reports.

# Overview of Advanced Automation For In-Space Vehicle Processing Study

- Study is part of SSF Advanced Studies Program
- Three year study began in FY 1989
- Primary study objectives

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- Identify suitable processing tasks to be automated (physical & non-physical)
- Determine hooks & scars required to support evolved SSF on-orbit processing
- Determine impacts of automated processing operations (timelines, reduced labor, SSF resource requirements)
- Assess required automation technologies

## Overview of Autonomous Diagnostic Checkout Task

The Advanced Automation study has struggled with the issue of determining computing resources and the resulting Hooks and Scars required to perform autonomous or semi-autonomous cognitive processing tasks. This issue has been addressed in each of the past three years. However it has been extremely difficult to establish any specific methods or results. The reason for this is the spacecraft to be processed are in a conceptual phase only at this time, and thus the system and processing details are non-existent. This makes it especially difficult to provide details for such high-level tasks such as planning and diagnostics. Furthermore the software environment and architecture for the SSF Data Management System, has not been completely defined yet either.

Thus, in order to provide more specific results this year, the study has begun to focus on a more specific, less encompassing task. The problem of complete system checkout and diagnostics of a vehicle after it has been readied for launch is an ideal task for nearly complete automation. Because this task will be similar for both exploration and existing vehicles, such as the Space Shuttle, detailed information can be obtained. Thus, computer requirements for complete on-orbit checkout of a vehicle, assuming a single IVA astronaut monitoring the testing, have been determined. These requirements assume a baseline computer system is available either on board SSF, on board the vehicle or possibly on the ground. Thus, only those requirements which are specific to autonomous checkout are determined.

# Overview of Autonomous Diagnostic Checkout Task

- Identify the vehicle processing tasks that can benefit from AI technologies
- Develop a methodology primarily focused on determining the additional computer system memory requirements for autonomous diagnostic checkout
- Estimate the additional computer system requirements for on-orbit diagnostic checkout of exploration vehicles
- Provide input to DMS evolution requirements and studies

## Assumptions

A number of assumptions have been made to confine this task and make possible the determination of specific numerical requirements. Most of these are straightforward. Note that task times for both the case of human test conductors performing each step and autonomous checkout are identical for a majority of system tests. This is true because the total checkout task time consists mostly of physical processes and measurements. That is the time to issue a system command or diagnose a problem is usually much less than waiting for a tank to fill or a sensor reading to settle etc.

# Assumptions

- Focus on autonomous diagnostic checkout of LTV at SSF
- Computer memory forecasts are in addition to baseline DMS requirements and are independent of where the expert systems reside (ie. on SSF, on LTV, or on the ground)
- All test support equipment configuration and hookups are completed prior to conducting any automated diagnostic checkout procedures
- The memory forecasts do not include additional requirements for diagnosing problems with support equipment
- Automated diagnostic checkout test will take same elapsed time as manual diagnostic test, and only one crew member is required to supervise the automated diagnostic checkout expert systems
- All detailed test analyses based on expert system technology

## Analysis Methodology

A detailed method consisting of various levels of detailed analysis, extrapolations and generic guidelines has been developed to analyze and determine automated diagnostic testing requirements . This can be applied to any proposed system which can be modeled as a set of analogous currently built systems for which well documented checkout procedures exist. The requirements are based on the use of expert systems technology being used to perform the automated diagnostic procedures. The basic results provide the number of logic rules and object data facts necessary to perform the required test. This information is then used to predict computer resource requirements such as processor and mass storage memory.

The method consists of 4 specific tasks or components to provide the final requirement data:

1. First the processing tasks of an entire system assembly or refurbishment process are analyzed to determine which tasks are purely diagnostic tasks that are beneficial to be automated. Because a single IVA based operator can completely monitor the checkout test the required on-orbit labor is reduced.

2. One or more analogous, currently existing systems are then identified. The analogous ground task(s) is then analyzed and a complete set of rules and full knowledge base for the one system or test item is developed. From this example coded knowledge base the memory requirements per object or specific test item are determined.

3. The relative sizes of all vehicle systems are then determined by examining the relative sizes of all analogous systems. The relative sizes of shuttle systems is determined from the relative sizes predicted by STS math model sizes. The math models are used to simulate system performance for training and accurately represent total number of components and complexity in each system.

4. Other existing AI systems currently in field use are then analyzed to provide additional missing data items. Because these systems actually exist, the size and complexity of the physical systems they operate on are well known. Also, because they are in use, the overall computer requirements are well known. Thus they provide, in a sense, a reality check to the predicted requirements determined for on-orbit checkout. These existing ground systems can also be used to estimate factors such as graphics display and user interface requirements, operating systems and other factors which represent requirements in addition to those requirements due to specific rules and knowledge.

# Analysis Methodology

## Analysis of On-Orbit Processing Tasks

- Analyze LTV initial assembly & turnaround flows for diagnostic test that can benefit from expert systems
- Estimate on-orbit manpower savings

## Analysis of Analogous Ground Test

- Select representative LTV diagnostic test to analyze (ECLSS)
- Identify & analyze analogous ground task
- Develop rules & knowledge base for a specific test
- Calculate core rule set memory reqmts for sample knowledge base

## Analysis of Shuttle Math Models

- Analyze Shuttle subsystem math models
- Apply relative sizes of Shuttle math models to similar LTV subsystems
- Calculate memory reqmts for integrated LTV knowledge base by extrapolating ECLSS requirements to all LTV subsystems

## Analysis of KSC AI Systems

- Analyze existing KSC AI systems for relative sizes of knowledge base, memory reqmts, # of components & measurements monitored, & exception processing requirements
- Obtain memory reqmts for knowledge base overhead

Estimate total computer memory reqmts for autonomous LTV test & checkout

**Note: Shaded boxes denote major results**

# Analysis Methodology
## *Analyze On-Orbit Processing Tasks*

- **Each LTV processing procedure/task was assigned one of the following rankings**

  ***Category 1*** - A procedure/task that is a physical task done by an astronaut or telerobot

  ***Category 2*** - A procedure/task that could benefit from advanced AI technology (ie. vision systems, pattern matching, inspection) beyond the scope of this expert system analysis

  ***Category 3*** - A procedure/task that is strictly a diagnostic test and/or checkout that can be accomplished by an expert system

  ***Category 4*** - A procedure/task that is primarily an IVA astronaut activity (ie. power vehicle down, take pictures) that could benefit marginally by using AI/expert systems

- **An estimate of manpower savings for all Category 3 tasks was calculated as a result of utilizing only one IVA astronaut to supervise expert system vs. baseline 2 - 3 astronauts per checkout task**

# Analysis Methodology

## *Analyze an Analogous Ground Task*

- Analyze the diagnostic checkout procedures for the Atmospheric Revitalization and Pressurization Control System (ARPCS) of the Environmental Control and Life Support System (ECLSS)

- Interview the Shuttle ECLSS system engineers on standard diagnostic checkout procedures and exception processing procedures (troubleshooting)

- A sample knowledge base was built for an ARPCS cabin pressure relief valve test as documented in OMI (Operations & Maintenance Instructions) V1020

# Analysis Methodology
## *Why Analyze the ECLSS and ARPCS?*

- The ECLSS is a good representative vehicle system (303 fluid components and 330 instrumentation measurements)

- The ARPCS is a complex subsystem (22.5% of the measurements and components in ECLSS) for which a sample knowledge base could be encoded

- Forecasts of memory requirements could be calculated for ARPCS and ECLSS as a result of building the sample knowledge base

- Memory estimates obtained for ARPCS and ECLSS could be extrapolated to all vehicle systems

- Provides a real-world example of diagnostic checkout procedures on a space vehicle

# Analysis Methodology
## *Analyze Current AI Systems at KSC*

- **Knowledge-Based Autonomous Test Engineer (KATE)**
  KATE is an excellent example of an AI system that monitors gauges, valves, flow rates, and pressures. It was observed while monitoring the LOX tanking process of the External Tank during the launch countdown for the STS-40 mission.

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- **Operations Analyst Expert System (OPERA)**
  OPERA is an intelligent operator assistant that monitors Firing Room hardware. It reacts to problem situations and notifies the Master Console Operator when hardware failures are detected.

- **Expert Mission Planning and Replanning Scheduling System (EMPRESS)**
  Expert system that schedules Shuttle resources at KSC. A significant portion of the knowledge base deals with handling exception processing.

- **Each system provided data on the relative sizes of the knowledge bases, memory requirements, disk storage requirements, and the number of components and measurements monitored.**

# Analysis Methodology
## *Analyze Math Models of Shuttle Systems*

- Shuttle subsystem math models are used for training and certification of Firing Room console operators

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- They are based on the number of components and measurements in each vehicle system, and therefore reflect the relative size and complexity of each system

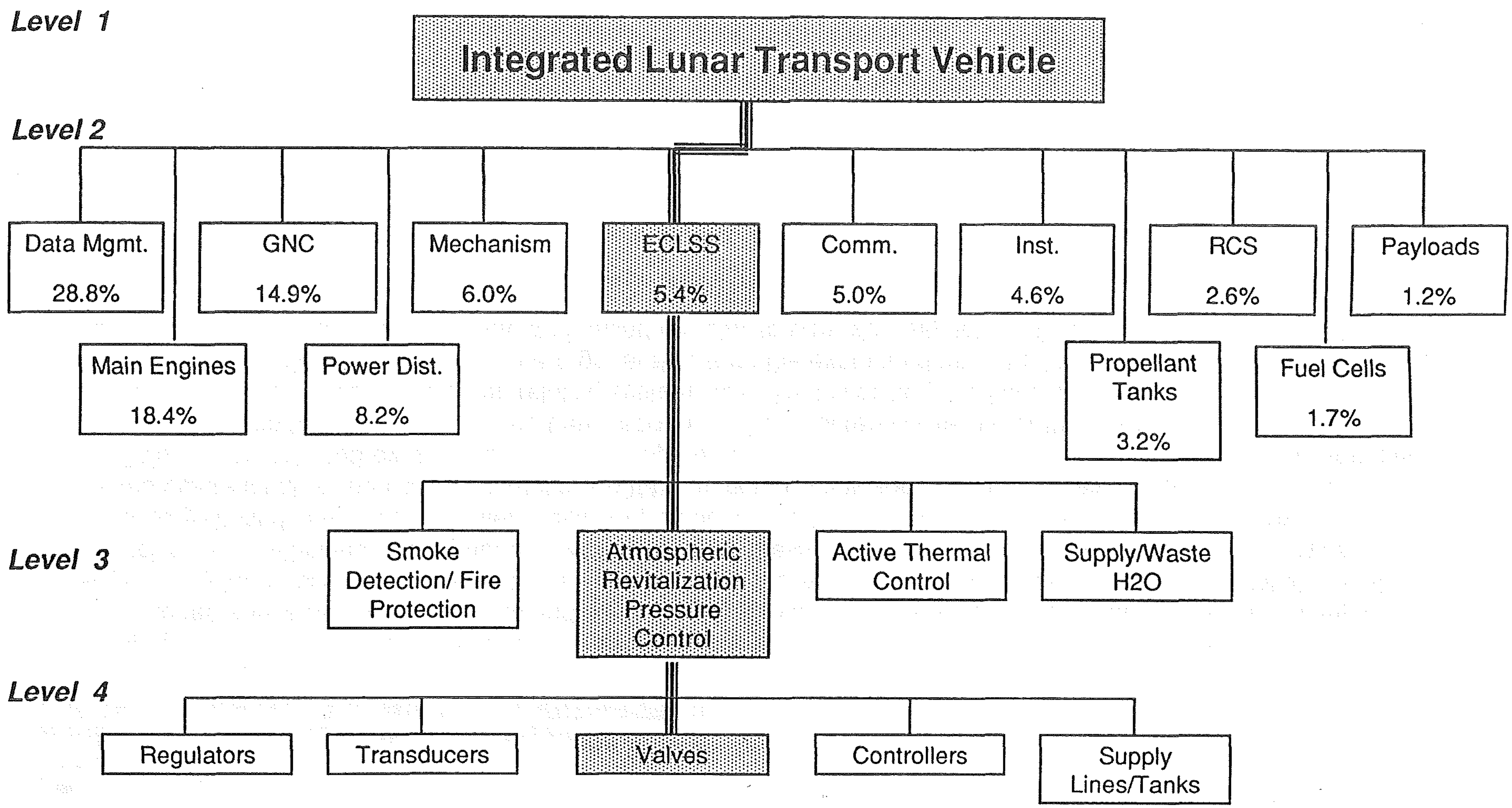
- A repartitioning of the current Shuttle vehicle systems into projected vehicle systems of the future LTV was conducted to accommodate for differences between the two vehicles

- The relative size of each vehicle system was needed to extrapolate the computer memory requirements for all vehicle systems once the ECLSS estimate was obtained

## Approach For Estimating System Requirements

Although analogous systems in use today exist for every system in an exploration vehicle, and thus specific checkout requirements exist, due to the size and number of systems, it is far too laborious to actually develop sample knowledge bases for each system. Instead one specific, highly representative task has been analyzed in detail. In this case a specific valve within the Atmospheric Revitalization and Pressure Control System (ARPCS), a subsystem of the Environmentally Closed Life Support System (ECLSS), on board the Shuttle was analyzed in detail. Based on documented Operational Maintenance Instructions (OMI), an actual knowledge base for a valve checkout task was created. This is accomplished by developing a PC computer based expert system using the ECLIPSE expert system shell tool. The requirements for this single test are then used to predict total requirements for the ARPCS which are then extrapolated to the entire ECLSS based on relative system size. That is basic guidelines showing number of rules and memory required per object and system test are generated from the example data. The total requirements for each of the other vehicle systems are then simply computed based on relative size with respect to ECLSS.

# Approach for Estimating Expert System Requirements For LTV Diagnostic Test & Checkout



## Results Of Building Sample Knowledge Base

A single valve test, the Cabin Pressure Relief Valve, within the ARPCS subsystem of the Shuttle ECLSS system was coded into an actual expert system knowledge base on a PC. The nominal test, in which no unexpected results or problems occur, was based on an actual Operation and Maintenance Instruction (OMI) in use today. The results provide guidelines and expressions to predict the total memory requirements of a knowledge base of any system whose number of components and required measurements are known. Results show that each object in the system requires three facts to represent its state. An object may be a component or a measurement. Facts are simply data items about an object such as its state, (ie. open, closed, on etc.) or a minimum or maximum value for a measurement for example. Rules define either the condition of the system based on the facts or they control the flow of the test. Any test requires a standard set of steps such as start systems, read data items etc. Each test then has specific rules which make up the remainder of the flow for a nominal test. Memory is also required to access current and historical sets of specific fact data items stored in a database. Memory is also required to store the actual expert system inference engine which sequences or applies the rules for a given knowledge base.

# Results of Building a Sample Knowledge Base For Cabin Pressure Relief Valve Test

- Results of this exercise showed that there are approximately:
  - **3 facts per object** (an object is defined as a measurement or component)
  - **40 bytes per fact** (a fact is for example "relief valve 1 is open")
  - **270 bytes per rule**
  - **15 Generic Baseline Rules required per test sequence**
  - **Test Specific Rules required per test = 20% times the number of objects**
  - **70K of memory required for database access**
  - **282K of memory required for an inference engine**

## Results Of Exception Processing Analysis

The OMI procedures, and the example knowledge base developed based on these, do not include the knowledge and steps taken when failures occur during testing. To accurately predict realistic requirements for a complete checkout system the ability to handle exceptions from the nominal test case must be accounted for. In order to analyze this portion of the system the exception handling rule requirements were determined by examining the ARPCS system as a whole. Interviews with NASA test conductors for this test were carried out to obtain these results. They provided an indication of which systems are most likely to fail and how often exceptions occur during typical testing. For problems which occur frequently, specific test sequence flows developed by the conductors were used to predict exception requirements. It should be noted that this is in essence expert knowledge and experience. Because the exceptions are handled on a case by case basis no documentation for these flows exists. This analysis provides data in the same form as the Relief Valve test but is given in total for the ARPCS system. The total numbers for exception handling in the entire ECLSS checkout are then extrapolated based on the relative size of ARPCS within ECLSS.

# Results of Exception Processing Analysis in ARPCS & ECLSS

- ARPCS was analyzed to determine the procedures/tasks that are carried out when a problem is encountered while conducting a diagnostic test
- Procedures and knowledge obtained from expert interviews with NASA test engineers
- Results of this analysis showed that within the troubleshooting procedures for ARPCS there are approximately :
  - 79 objects
  - 237 facts
  - 120 Generic Baseline Rules
  - 656 Test Specific Rules

# Results of Exception Processing Analysis in ARPCS & ECLSS (cont.)

- Since ARPCS comprises 22.43% of ECLSS, the exception processing requirements were extrapolated for the entire ECLSS

- Results of this extrapolation indicate that within the troubleshooting procedures for ECLSS there are approximately:

  - 352 objects
  - 1,056 facts
  - 535 Generic Baseline Rules
  - 2,925 Test Specific Rules

# Results of Analyzing Current AI Systems at KSC

- Analyzing OPERA revealed that the application specific graphical user interface (GUI) takes up approximately 30% of the total knowledge base requirement

- The analysis of EMPRESS showed that 73% of the knowledge base consisted of rules to handle exception processing

- While analyzing KATE, it was learned that approximately 400MB of disk storage is required by the Shuttle Launch Processing System (LPS) to store 4 - 6 hours of real-time vehicle data

# Breakdown of Memory Requirements For ECLSS Knowledge Base

| Factor | Memory | How Obtained |
|---|---|---|
| *Core Object Memory* | 76.0K | (633 components in ECLSS) * (3 facts per object) * (40 bytes per fact) |
| *Generic Baseline Rule Memory* | 4.1K | (15 Generic Baseline Rules) * (270 bytes per rule) |
| *Test Specific Rule Memory* | 34.2K | (633 objects) * (20%) * (270 bytes per rule) |
| *Exception Proc. Rule Memory* | 980.0K | (219.8K memory required for exception processing in ARPCS) / (22.43% - which is the relative size of ARPCS to ECLSS) |
| *Database Access* | 70.0K | (Estimated from prior experience in building expert systems) |
| *Application Specific GUI Memory* | <u>350.0K</u> | (76.0K + 4.1K + 34.2K + 980.0K + 70.0K) * (30% for application specific GUI) |
| **Total For Knowledge Base** | 1.51 MB | |

# Computer Memory Requirements For ECLSS

**1.51 MB for ECLSS knowledge base**

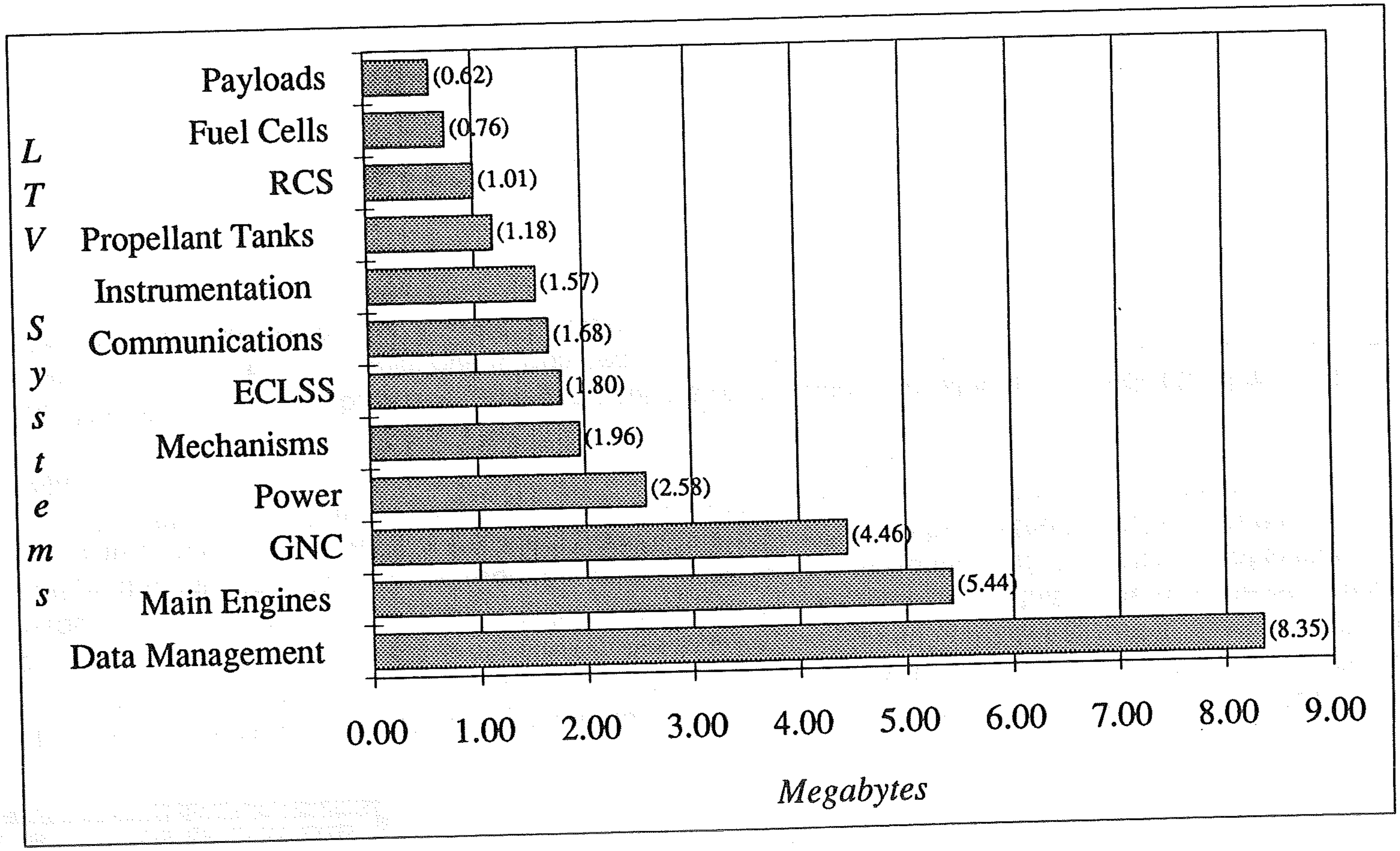
*plus*

**.28 MB for inference engine**

*equals*

**1.80 MB memory required to run ECLSS expert system**

# Graph Illustrating Memory Requirements When Running A Single Expert System At Any One Time



## Summary Of Requirements

The primary result of this analysis is the memory required per LTV system to represent autonomous checkout knowledge. The results have been obtained by examining the ECLSS system in detail and extrapolating the results, based on relative system sizes (number of components and complexity), to the other systems. If all systems are run simultaneously a total of 30MB of memory would be required. However, although this is the way the Shuttle is monitored and tested prior to launch, it may not be required for On-Orbit vehicle systems. Some partitioning of system tests may be allowable. This reduce the overall requirement to a number somewhere between the 8.4MB required for the minimum system and the 30MB total. Further analysis will be required to determine what if any test partitioning would be acceptable.

The IVA labor savings is based on previous analysis by this and other studies to predict total manual checkout labor requirements. The savings are totally due to only requiring one supervisor when using an autonomous system as opposed to three test conductors for the manual case.

# Summary of Requirements for Autonomous Diagnostic Checkout

- 8.35 MB memory required to execute largest LTV expert system (Data Management)
- Approximately 30MB of memory required to execute all LTV expert systems simultaneously
- 400 MB disk space required for recording 4 to 6 hours of real time vehicle data
- 54% IVA manpower savings for LTV test/checkout using automated diagnostic checkout procedures with single astronaut supervising (160 man-hours for initial assembly and 816 man-hours for refurbishment saved)

## Recommendations For Additional Analysis

Two primary extensions of this analysis to provide more detailed results and justification for computer requirements are possible. First, the guidelines used to predict total requirements for each system based on its number of components is based on a single sub-system test example knowledge base. This analysis could be extended by developing example knowledge bases for other systems. The assumption that expert system technology would be used to perform autonomous diagnostics may also be affecting the results. There are a number of other emerging artificial intelligence technologies which may provide significant advantages and a different set of computer resource requirements. For convenience the technologies which could perform diagnostics are defined below:

*Expert System* - an intelligent computer system that uses knowledge in the form of rules to solve problems that are difficult enough to require significant human expertise for their solution.

*Model-Based System* - a computer system that takes knowledge about the components of a particular system and applies search and algorithmic techniques to evaluate the performance between the model and real system.

*Neural Network* - a computer system that can be "trained" to classify information and matches the functionality of the human biological decision making process in a very fundamental manner.

*Fuzzy Logic* - Systems which are extension of expert systems which involve degrees of probability applied to specific rules and conclusions. They are better at handling real world occurrences which are approximate such as marginally working, working well but not perfect etc.

The overall impacts of using various technologies, or even how to compare requirements of these systems in a general way is not known at this time. Furthermore the results provided here are only for system diagnostics. The same techniques or similar analyses must be done to determine computer requirements for all advanced automation tasks.

# Recommendations for Additional Analysis

- Compare and/or contrast the use of rule-based systems, with new and/or different AI technologies. For example; What would be the impact of using model-based systems versus rule-based systems?; Are neural networks applicable?

- Conduct a detailed analysis of the number of measurements and components in other vehicle systems (ie. power distribution, fuel cells, reaction control systems, etc.) to refine the relative sizes of the LTV systems.

- Develop additional sample knowledge bases to validate memory factors

- Develop optimal, acceptable partitioning of system checkout tests to be run an a sequential manner to reduce overall requirements

- Perform expert system analysis for test support equipment (GSE fails more frequently than flight hardware)

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13. ABSTRACT *(Maximum 200 words)*
This report contains the individual presentations delivered at the Space Station Evolution Symposium in League City, Texas, on August 6, 7, & 8, 1991. Personnel responsible for Advanced Systems Studies and Advanced Development within the Space Station Freedom Program reported on the results of their work to date. The results of SSF Advanced Studies provide a road map for the evolution of Freedom in terms of user requirements, utilization and operations concepts, and growth options for distributed systems. Regarding these specific systems, special attention is given to: highlighting changes made during restructuring; description of growth paths thru the follow-on and evolution phases; identification of minimum-impact provisions to allow flexibility in the baseline; and identification of enhancing and enabling technologies. Products of these tasks include: "Engineering" fidelity demonstrations and evaluations of advanced technology; detailed requirements, performance specifications, and design accommodations for insertion of advanced technology; and mature technology, tools and applications for SSF flight, ground and information systems.

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